Groundwater Flow Model of the Santa Cruz Active Management Area Microbasins International Boundary to Nogales International Wastewater Treatment Plant Santa Cruz County, Arizona

ARIZONA DEPARTMENT OF WATER RESOURCES

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Executive Summary

Arizona's heavy reliance on groundwater has resulted in significant overdraft of groundwater resources in many areas of the state. In 1994, the State legislature recognized the unique hydrologic issues facing the Upper Santa Cruz River Valley and created the Santa Cruz Active Management Area. Several distinct hydrogeologic areas comprise the Santa Cruz Active Management Area. This report addresses the area in the valley along the Santa Cruz River from the International Boundary to the Nogales International Wastewater Treatment Plant, an area commonly referred to as the microbasins. The microbasins are described as a series of four small alluvial basins surrounded by impermeable or very low permeability formations, either bedrock or Nogales Formation. Hardrock outcrops serve to separate the basins from each other.

The Arizona Department of Water Resources has developed a regional groundwater flow model to assist in the understanding of the complex hydrologic system. Additionally, the model will aid the Santa Cruz Active Management Area in determining if they are achieving their management goals and with the analysis of future management strategies.

An analysis of the hydrogeology and water resources was conducted for the microbasin area. Three lithologic units were identified as the younger alluvium, older alluvium and Nogales Formation. Hydraulic characteristics of each of these units were quantified. Surface water data were collected including streamflow measurements for five locations on the main stem of the Santa Cruz River. Groundwater pumpage data was collected and summarized.

A regional model was constructed using the U.S. Geological Survey computer code MODFLOW and was used to simulate hydrologic conditions from October 1997 through September 2002. The active model domain encompasses approximately 40 square miles. The model has approximately 2,500 active model cells distributed among three layers, each layer simulating a distinct hydrogeologic unit. Model cells are 660 feet by 660 feet or 10 acres each. The model simulates the hydraulic interconnection between the Santa Cruz River and the groundwater system.

Model layer one corresponds to the younger alluvial aquifer occurring along the course of the Santa Cruz River. It is comprised of generally unconsolidated sands and gravels with occasional lenses of silt and clay and readily yields water to wells. Model layer two corresponds to the older alluvial aquifer, which composes the valley floor between Mount Benedict and the Patagonia Mountains. Model layer three corresponds to the Nogales Formation that underlies the older alluvium and outcrops at the surface at various locations. The older alluvium and Nogales Formation do not readily yield water to wells.

The model was calibrated to transient-state groundwater flow conditions. Several criteria were used to determine the accuracy of the model. These criteria included comparing measured water levels to final model-simulated water levels, comparing hydrographs from selected wells to model-simulated water levels, comparing model-generated volumetric water budgets to conceptual estimates, and comparing model-simulated surface water flow to conceptual estimates and field measurements.

A sensitivity analysis was conducted to determine how sensitive the model solution is to uncertainty in each input variable. The model is most sensitive to time discretization as the groundwater system in the primary aquifer is heavily influenced by recharge from flow in the Santa Cruz River.

In general, the groundwater flow model developed for the Santa Cruz River microbasins appears to reasonably simulate groundwater conditions in the younger alluvial aquifer. Results indicate that the younger alluvium, particularly the Kino Springs and Highway 82 microbasins, are recharged almost solely from discharge in the Santa Cruz River. The older alluvium and Nogales Formation contribute very little recharge to the younger alluvium. Consequently, recognizing the significance of climatic patterns in the area is central to the success of future management strategies.

Data are inadequate in the older alluvium and Nogales Formation to draw any specific conclusions or use the model reliably as a predictive tool in those areas.

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Acknowledgements

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Disclaimer

For purposes of this report "surface water": refers to water above land surface, including storm run-off and baseflow along the Santa Cruz River and its tributaries. The term "groundwater" refers to water in the subsurface, i.e., water measured in wells. It should be emphasized that any references or inferences to groundwater, or the younger alluvium (or any other hydrogeologic unit) are not meant to be legal determinations and should not be interpreted as such. For this report, the terms "surface water" and "groundwater" are used only for ease of reference and convention.

In addition, the model presented in this report is only an approximate representation of a complex regional groundwater flow system. Because of the complexity, it was necessary to make simplifications in order to develop and calibrate the model. It is important that the readers understand and interpret the model within the context of the underlying assumptions and generalizations.

Chapter 1 - Introduction

Arizona's heavy reliance on groundwater has resulted in significant overdraft of groundwater resources in many areas of the state. In 1980, the Arizona legislature implemented the Groundwater Code in order to ensure a secure water supply for the future. The Groundwater Code identified four areas within the state where water management is required to address the impacts of widespread water withdrawals. The areas are referred to as Active Management Areas (AMA) and were identified as the Prescott, Phoenix, Pinal and Tucson AMAs. In 1994, the legislature recognized the unique issues of the Upper Santa Cruz River Valley and created the Santa Cruz AMA (SCAMA). It was formed from the southeastern portion of the Tucson AMA and lies between the International Boundary and the Santa Cruz/Pima County line. See Figure 1-A,

The Santa Cruz AMA was given a dual goal by the Arizona State Legislature. The first component of the goal is to maintain safe-yield on an AMA–wide basis. Safe-yield is defined by the Groundwater Code is "to achieve and thereafter maintain a long-term balance between the annual amount of groundwater withdrawn in an AMA and the annual amount of natural and artificial groundwater recharge in the AMA." A.R.S. §45-561(12). The volume of groundwater that can be withdrawn while maintaining safe-yield in the AMA is not a fixed amount; it may change with variations in recharge. The second component is to prevent local water tables from experiencing long-term declines. This goal is defined as maintaining target water levels that can vary by hydrologic segments, which must be maintained on average, subject to natural fluctuations (ADWR, 1999).

In order to determine if the Santa Cruz AMA is achieving its goals the Arizona Department of Water Resources has developed two regional groundwater flow models in the area. This report describes the model area from the International Boundary to the Nogales International Wastewater Treatment Plant (NIWTP). The area is commonly referred to as the

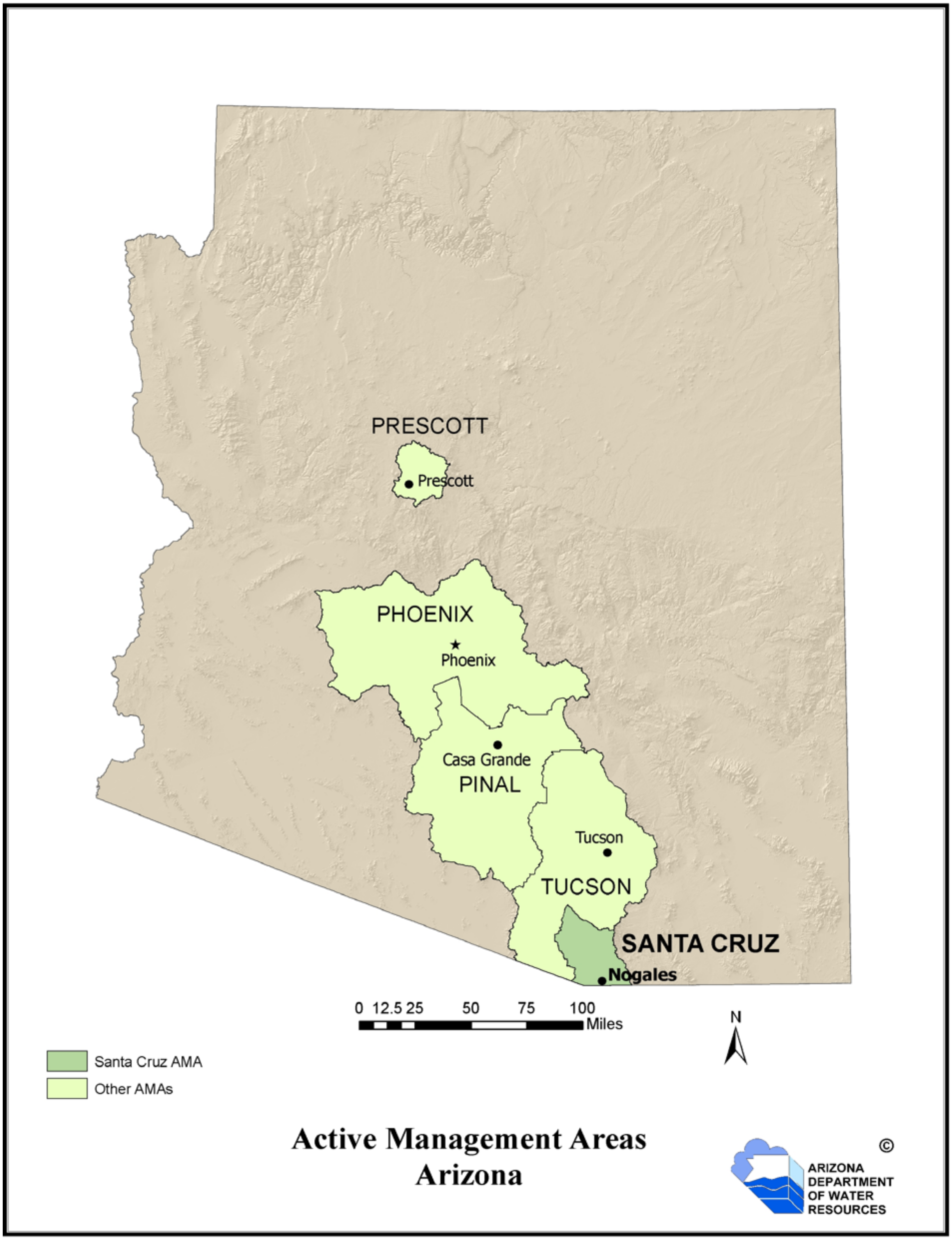

Figure 1-A. Map showing location of Arizona Active Management Areas.

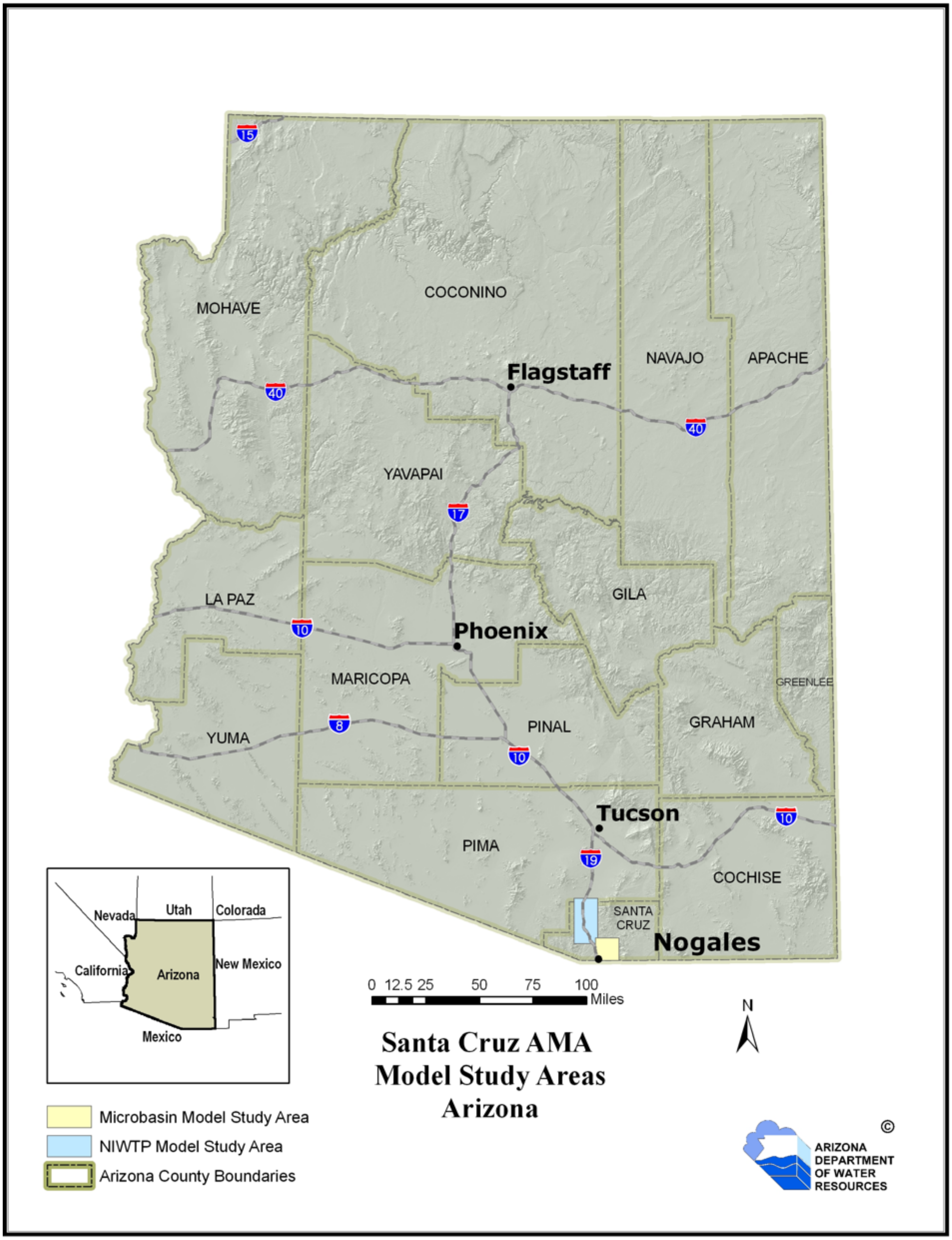

Figure 1-B. Map showing Model Study Areas.

“microbasins”. The second model (Nelson, 2007) enco mpasses the area from the NIWTP to the Santa Cruz/Pima County line (and in this report is referred to as the NIWTP model). The model study areas are restricted to the alluvial fill aquifers between the surrounding mountains with special emphasis on the alluvial fill aquifer adjacent to the Santa Cruz River. The surrounding mountains provide a natural physical boundary to the groundwater flow system.

Goals and Objective

The primary goal of the Santa Cruz AMA groundwater modeling study is to develop an analytical tool capable of quantifying the effects of various groundwater management programs on the groundwater supplies within this study area and to learn more about how the hydrologic system operates. The general objectives are to develop a numerical model that effectively simulates the groundwater/surface water interaction, accumulates all hydrologic, geologic, pumpage, and evapotranspirational data for the entire microbasin area into a single database format and provide analysis of specific predictive scenario model simulations that will assist in evaluating availability of supply. (Specific predictive scenario model simulations for evaluating availability of supply will be presented in a separate report.)

Purpose and Scope

The purpose of this report is to describe the geology and hydrology of the groundwater basin area referred to as the microbasins in the Santa Cruz AMA. The report documents the data collection, data analysis, and construction of the model study. It describes the numerical model that has been developed for the groundwater/surface water flow system for water years (October through September) 1997–2002. In addition, the report provides recommendations concerning future model updates, improvements, uses, and limitations.

Physiography

The Santa Cruz AMA is located in the Sonoran Desert in south-central Arizona. It includes 716 square miles in the Upper Santa Cruz River Valley and is principally concentrated around a 45-mile reach of the Santa Cruz River from the International Boundary to the Santa Cruz/Pima County line. The microbasin model encompasses the alluvial valley from the International Boundary on the south to Sonoita Creek on the north. It is bounded on the east by the Patagonia Mountains where the elevation reaches 7,221 feet above means sea level (amsl) at Mt. Washington, and on the west by a set of highly faulted hills with a maximum elevation of 4,565 feet (amsl) at Mt. Benedict. See Figure 1-C. The Santa Cruz River runs along the western edge of the valley and has cut a smaller alluvial valley within the broader older alluvial valley. The smaller valley ranges in width from just a few hundred feet at the hardrock constrictions, such as Guevavi Narrows, to approximately 3,900 feet near Highway 82 (Simons, 1974). The Santa Cruz River is the main source of recharge for the younger alluvial aquifer. There are no towns within the microbasin model area; however, the City of Nogales owns wells within the area that supply water for municipal purposes. Surface water inflow to the model area is measured at U.S. Geological Survey Gage (09480500), Santa Cruz River near Nogales. The gage is located approximately 0.8 miles north of the International Boundary. The drainage area is 533 square miles of which 348 are in Sonora, Mexico. The remainder of the drainage area is in the San Raphael Valley in Arizona where the headwaters are located. The microbasin model drainage area is approximately 110 square miles (Carollo, 1964). The drainage area at the Santa Cruz County line is approximately 1,466 square miles (Andersen, 1955).

Vegetation

The low floodplains associated with the Santa Cruz River are vegetated by Fremont cottonwood and Goodding willow. Mesquite bosques, netleaf hackberry and Mexican elder occur further away from the river. Cienegas, sacaton, giant sacaton, and alkali sacaton grasslands, as well as riparian scrublands of seepwillow, rabbit brush and burro brush are present (ADWR, 1994). Grasses and small brush cover the bajada slopes of the alluvial valley. Riparian vegetation along the Santa Cruz River has experienced significant historical change. Riparian vegetation composition and density continues to respond to changes in land use, groundwater levels, fire suppression, cattle grazing, climate changes and possibly changes in water quality as exhibited in the area downstream of the NIWTP.

Climate

The Santa Cruz River Valley experiences a mild, semiarid climate with temperatures ranging from the average minimum of 43 degrees to an average maximum of 80 degrees. The average annual temperature in the Nogales area is 61 degrees (Western Regional Climate Center, 2005). The growing season begins in March and ends in October. The Santa Cruz River Valley receives the majority of its annual precipitation in two seasons, during the summer monsoon season July through August and in the fall/winter October, December, and January. Summer storms are generally local in extent, have high intensity but are of short duration. Winter storms are generally widespread and gentle, and are more intense in the mountains than in the valleys (Coates and Halpenny, 1954). Precipitation magnitudes and occurrences have fluctuated over time in the Santa Cruz River Valley. This variability is ultimately tied to long-term fluctuations in global weather patterns, including El Nino/ Southern Oscillation (ENSO) conditions (Webb and Betancourt, 1992), Pacific Decadal Oscillation (PDO), and NINO3 (Shamir, et al, 2005). Average annual precipitation is 17.43 inches (Western Regional Climate Center, 2005). A detailed study conducted by the Hydrologic Research Center (Shamir, et al, 2005) describes historical climate variability.

Previous Investigations

Several studies have been conducted in the microbasin modeling area and were useful in the development of the conceptual model. Studies conducted by Leonard Halpenny and Philip Halpenny of Water Development Corporation were invaluable. The Water Development Corporation has conducted several hydrological studies in the area since the 1950's that have contributed greatly to the hydrologic characterization of the Upper Santa Cruz River Basin. Their reports provided hydraulic parameters, as well as other important information such as

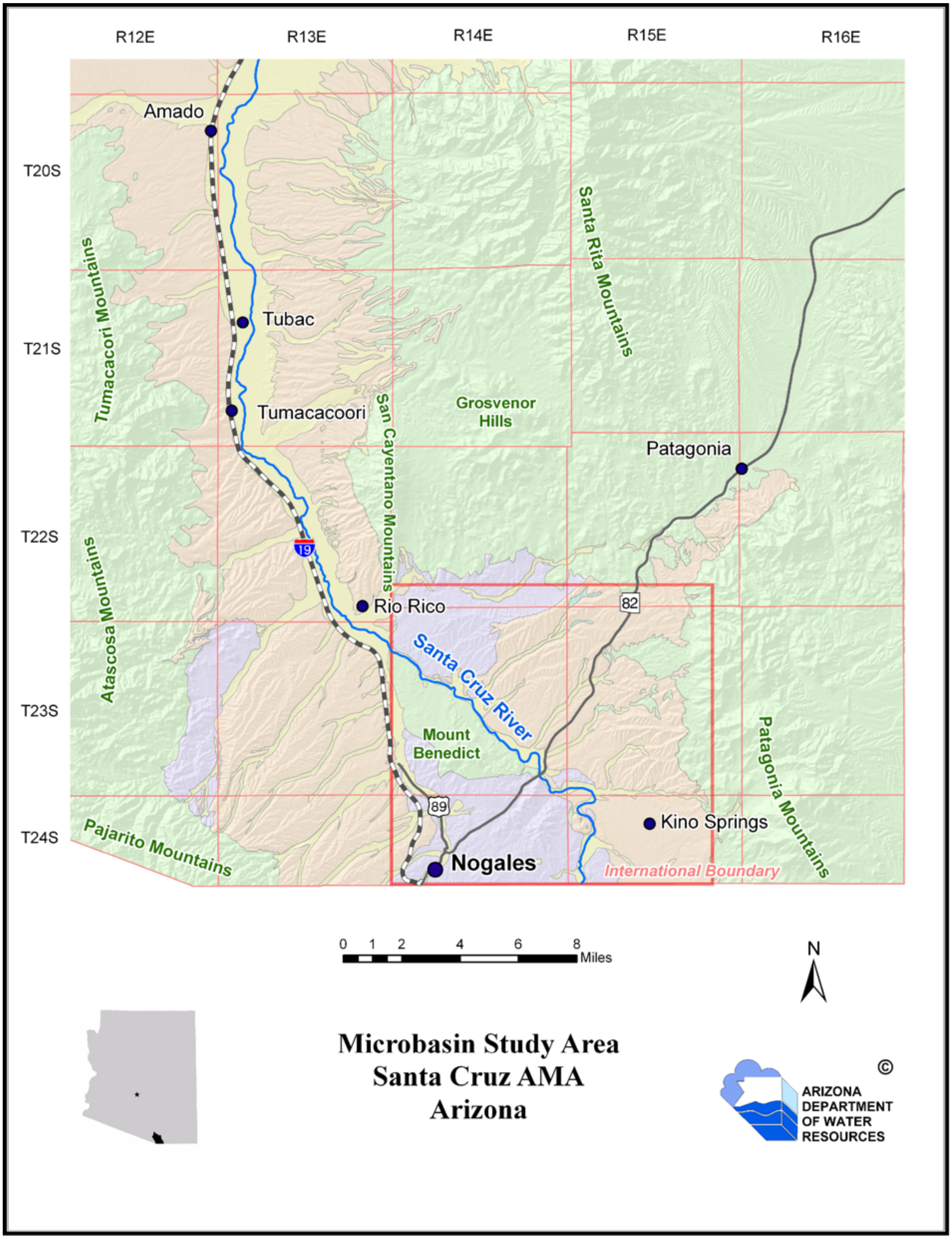

Figure 1-C. Map showing Microbasin Model Study Area and Santa Cruz AMA Physiography.

geology, water supply issues, land use, and cultural history. One particularly useful report is *Geophysical and Geohydrological Investigation of the Santa Cruz River Valley, Arizona, International Boundary to Mouth of Sonoita Creek* (1963). This report was prepared for the International Boundary and Water Commission to study the viability of a dam site at Burro Canyon. It includes geophysical studies, aquifer test data, permeability test data, underflow estimates and water budgets for the individual microbasins. The geophysical studies conducted in this report resulted in the identification of the small basins separated by outcrops of Nogales Formation and/or shallow bedrock, later to be referred to as microbasins. This study was highly relied upon and provided much of the information used to model the younger alluvial aquifer.

Two other reports by Water Development Corporation - *Evaluation of Adequacy of Groundwater Supply, Sonoita Creek Ranch* (1983) and *Basic Data Report Well No. D-24-15 8ada, Kino Springs* (1985) provided aquifer test data. Other reports by Water Development Corporation described water supply characteristics of the microbasins, particularly the Guevavi microbasin. These are *Renewable Urban Water Supplies, Nogales and the Microbasins of the Santa Cruz River, A Case of Natural Water Banking* (1991), and *The Geohydrological Environment of the Santa Cruz Basin from the International Boundary to the Wastewater Treatment Plant* (1990).

A study published by ADWR, *Buena Vista Ranch Development Study*, Putman, et al, (1983), provided information on an aquifer test conducted in the Buena Vista microbasin as well as a comprehensive overview of the hydrologic system in the general vicinity of the International Boundary to Guevavi Narrows. A report and maps by Simons (1974), *Geologic Map and Sections of the Nogales and Lochiel Quadrangles, Santa Cruz County, Arizona, U.S. Geological Survey Open-File Report 97-676, provided most of the geologic information.*

Chapter 2 - Geology

Basic Geomorphology

The microbasin model area is located in the Basin and Range physiographic province. It is characterized by elongated mountain ranges trending northwest – southeast separated by broad alluvial valleys. It is the result of a generally east-northeast / west-southwest crustal extension (Gettings and Houser, 1997). The upper Santa Cruz Valley is one of the narrower valleys in southern Arizona, only three to eight miles wide in the study area.

Rock Units

The alluvial valley in the microbasin area is bounded on the east by the Patagonia Mountains. The mountains are made up of a combination of rocks including igneous, metamorphic, volcanic and sedimentary ranging in age from Precambrian to Miocene (Simon, 1974). In the study area the predominant rock types exposed on the west side of the Patagonia Mountains are granodiorite (Tg) of Paleocene age and the Jurassic granite of Comoro Canyon (Jcg) which are probably the basement complex of the valley. These rocks are considered non-water bearing in this study.

The valley is bounded on the west and separated from the City of Nogales by a set of highly faulted hills of Nogales Formation (Tn) of Tertiary age and Jurassic quartz monzonite (Jb and Jbm) that forms Mount Benedict. The lower member of the Nogales Formation is in fault contact with the quartz monzonite. These rocks are also considered non-water bearing in this study.

The intermontane valley is filled with alluvial deposits. See Figures 2-A and 2-B. The oldest recognized alluvial unit in the study area is the Salero Formation (Ks) of upper Cretaceous age. The Salero Formation is only exposed in the study area in upper Guevavi Canyon and throughout an area referred to as Eagan Narrows. Simons (1974) describes the Salero Formation as mainly a conglomerate that consists of angular to subangular blocks of gray to pink coarse granitic rocks as much as 10 feet across set in a sparse sandy matrix; some greenish-gray arkosic sandstone and grit in well defined beds as much as five feet thick. The entire formation may be more than

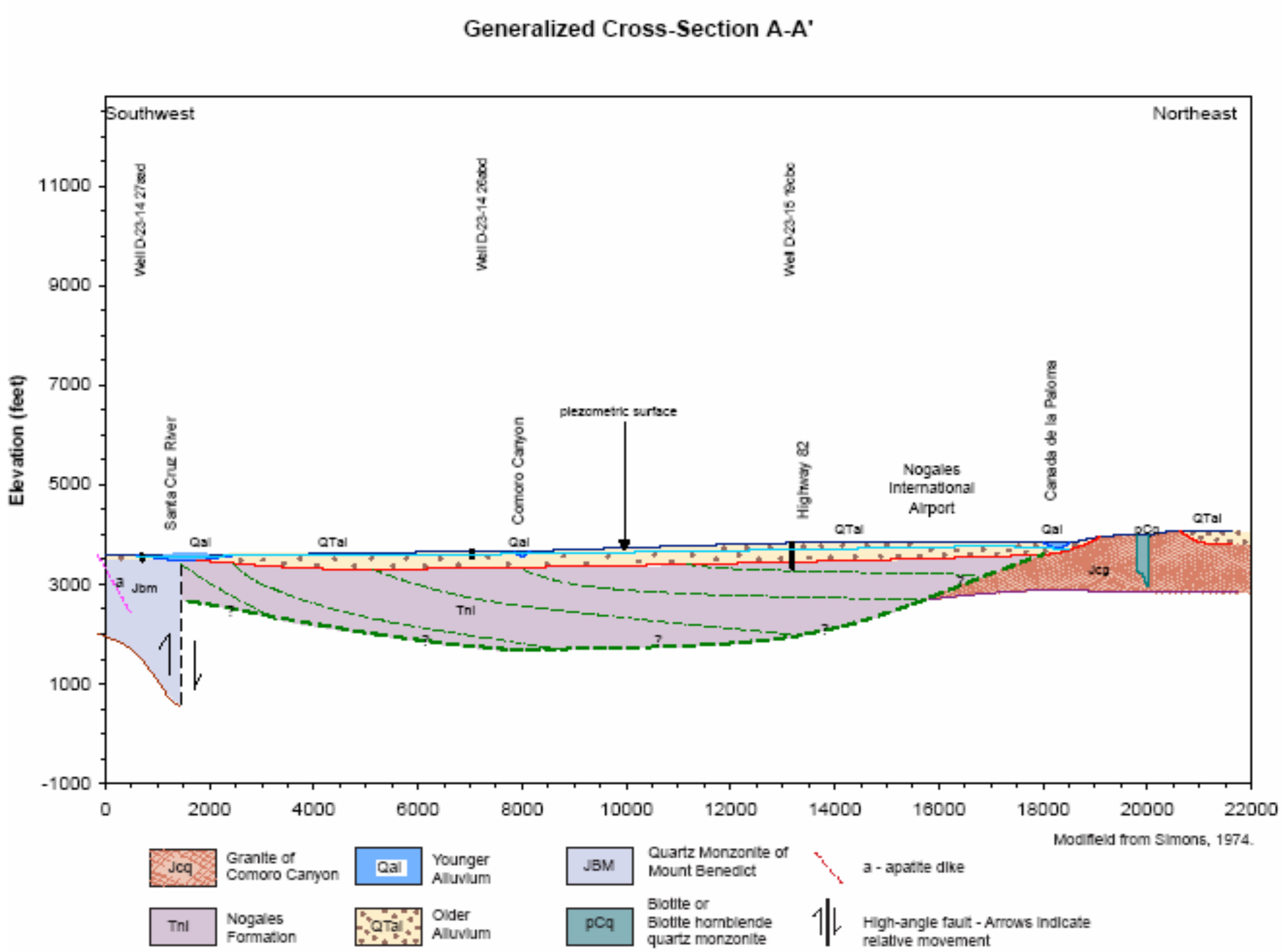

Figure 2-A. **Cross-section A-A'. (See Figure 2-C for location of cross-section.)**

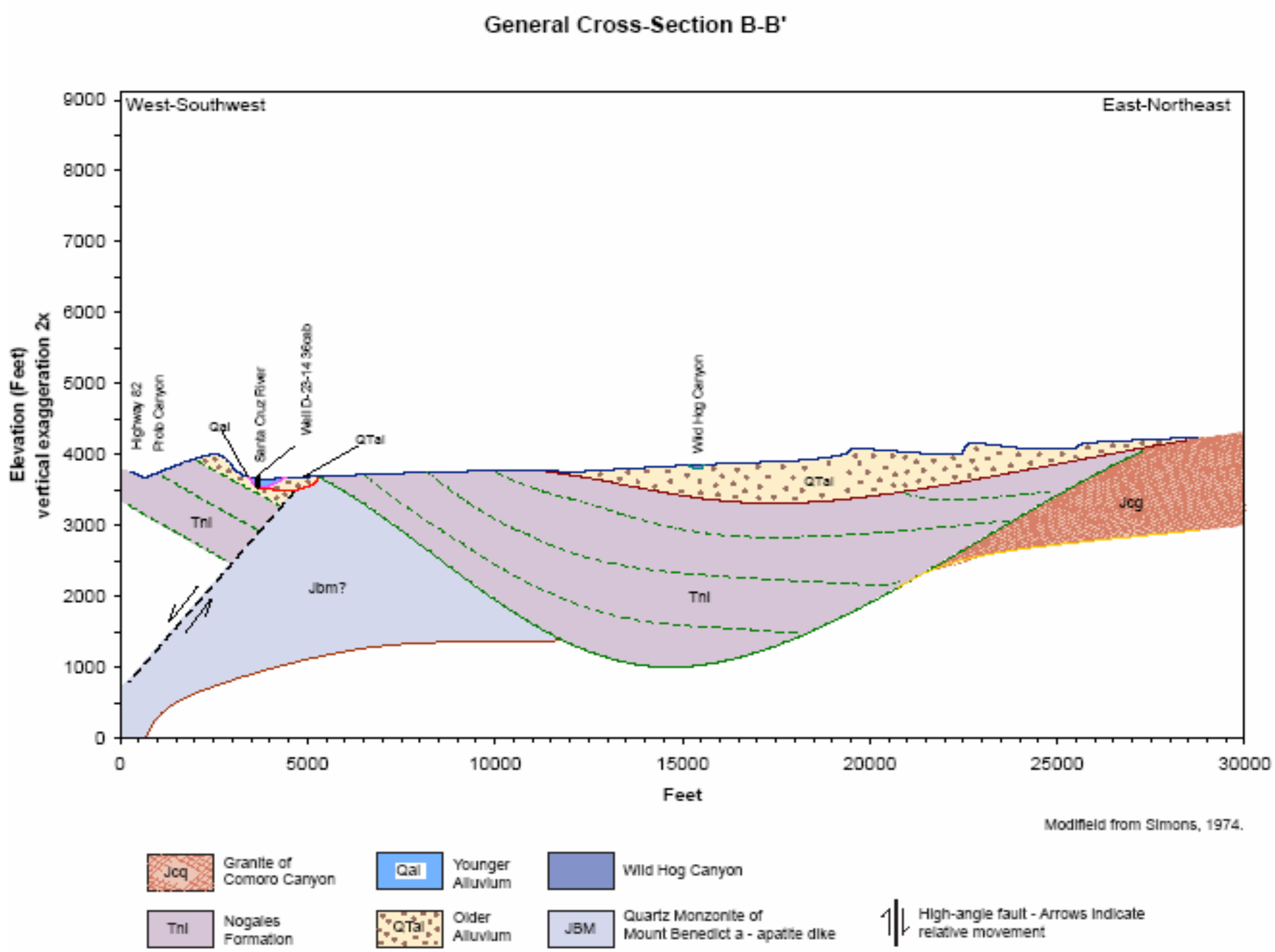

Figure 2-B. Cross-section B-B'. (See Figure 2-C for location of cross-section.)

2,000 feet thick. The Salero Formation is likely in fault contact with the Nogales Formation on the northwest side and southeast side of Guevavi Canyon (Halpenny, 1983; Simons, 1974).

The predominant alluvial unit in the study area is the Nogales Formation. The Nogales Formation is exposed in the hills between the City of Nogales and the Santa Cruz River. It is also exposed in the northern part of the study area. South of Guevavi Canyon (see Figure 2-C), the Nogales Formation unconformably overlies and is in part derived from the rocks of the Grosvenor Hills Volcanics. Simons (1974) recognizes three members of the Nogales Formation; the upper, middle and lower members and estimates total thickness of the formation to be as much as 7,500 feet between the Santa Cruz River and the City of Nogales. Simons (1974) generally describes the Nogales Formation as an epiclastic volcanic conglomerate containing abundant beds of sandstone and grit. Conglomerate clasts are silicic volcanic rocks of the Grosvenor Hills Volcanics. The Grosvenor Hills Volcanics are rhyodacitic and rhyolitic volcanic rocks of Oligocene age. They have likely completely eroded from the Patagonia Mountains and are not exposed in the study area. In some locations the Nogales Formation overlays or is interbedded with ash flows. The lower half of the formation is also interbedded with a basalt flow (Gettings and Houser, 1997; Simons, 1974). Simons (1974) and Halpenny (1963) also describe a brecciated zone within the Nogales Formation, a monolithologic sedimentary breccia made up of granitic material. This zone is exposed near the Highway 82 Bridge.

The Nogales Formation is overlain by a conglomerate identified by Simons (1974) as older alluvium (QTal) of late Tertiary and Quaternary age. Gettings and Houser (1997) describe the older alluvium as unconsolidated to poorly consolidated, although it is locally well cemented with calcite. The clasts are subangular to subrounded; sorting and bedding are poor to good. The composition of the clasts reflects the lithologies currently exposed in the nearby mountain ranges. The thickness of the older alluvium ranges from a few feet to at least 400 feet but generally the maximum thickness is around 200 feet (Putman, et al, 1983, Simons, 1974 and Harshbarger, 1979). It can be difficult to identify the contact between older alluvium and Nogales Formation as Gettings and Houser (1997) report: "In the few places where it is exposed, the contact of the Nogales Formation with the overlying upper basin-fill sediments is gradational within an interval of about 50 m (166.5 feet). The transition is marked chiefly by a decrease in consolidation upward and an increase in the lithologic variety of the clasts." In addition, Gettings and Houser (1997) report there are no datable materials or fossils in the older alluvium. However, based on similarities with sediments in other basins in the southern Basin and Range Province that contain datable materials, the age of the older alluvium is estimated to be upper Miocene, Pliocene, and possibly lower Pleistocene. The older alluvium is exposed over most of the study area. The older alluvium generally does not yield water readily to wells.

The younger alluvium (Qal) of Pleistocene and Holocene age lies along the course of the Santa Cruz River and its tributaries. Well logs indicate that it lies directly over the Nogales Formation or bedrock in the upstream portion of the model. In the Guevavi area it overlies a rather thick productive sequence of older alluvium and/or loosely consolidated Nogales Formation. The younger alluvium is generally comprised of sand and gravel with occasional lenses of silt or clay. It is mostly unconsolidated but may be locally well indurated. The thickness ranges from less than 40 feet to approximately 100 feet. Thickness may be slightly over 100 feet in the basin axes. The younger alluvium is the primary aquifer in the study area.

Geologic History and Structure

According to Simons (1974) the area is structurally dominated by faulting. See Figure 2-C. Simons reports as follows:

> "Prior to the deposition of the Nogales Formation the Jurassic Mount Benedict quartz monzonite, Paleocene granodiorite exposed in the Patagonia Mountains, and Oligocene Grosvenor Hills Volcanics were emplaced alternating with periods of erosion, uplift and conglomerate deposition. Uplift, accompanied and followed by long-continued depositions of fanglomerate, conglomerate, and sandstone of the Nogales Formation occurred along the west flank of the Patagonia Mountains. Just west of the Santa Cruz school the Nogales Formation rests unconformably on the quartz monzonite of Mount Benedict, but most contacts with rocks older than

> Gosvenor Hills Volcanics are faults or inferred faults. The lack of lacustrine and playa deposits indicates the valley was probably never closed.
>
> Uplift of the Mount Benedict area occurred resulting in large-scale normal faulting east, south and west of Mount Benedict; folding of the Nogales Formation east and northeast of Nogales. The Mount Benedict structural block is outlined by faults formed at this time; these faults involve rocks as young as the Nogales Formation and may have displacements of as much as 5000 feet. The Mount Benedict block is in fault contact with the Nogales Formation on the east along a northwest trend that is followed by the Santa Cruz River. Over much of the area south of the Mount Benedict block, beds of the Nogales Formation, which are believed to have dipped west or southwest originally, now dip gently to moderately east as a result of uplift and faulting.
>
> Major erosion and widespread alluviation occurred during the late Tertiary and Quaternary. Depositional products of this interval include older alluvium on present arroyo interfluves and younger alluvium along present stream courses."

Fieldwork conducted by Halpenny in 1963 indicated that the northeast-southwest trend of most of the tributary washes has developed along faults or fractures. Periods of deposition of alluvium have probably alternated with periods of erosion of alluvium in the upper Santa Cruz River valley. Tributaries of the Santa Cruz River are incised as much as 300 feet in the older alluvium. The Santa Cruz River in the microbasin area is likely structurally controlled by the fault that trends northwest-southeast; referred to by Gettings and Houser (1997) as the Mount Benedict Fault. This fault is on the east side of Mount Benedict where the quartz monzonite is in fault contact with the Nogales Formation. Coates and Halpenny (1954) noted that the Santa Cruz River does not follow the axis of the basin. The stream has been pushed westward because of the greater deposition of alluvial sediments from the east. The mountains on the east are much higher than those on the west and consequently receive heavier precipitation.

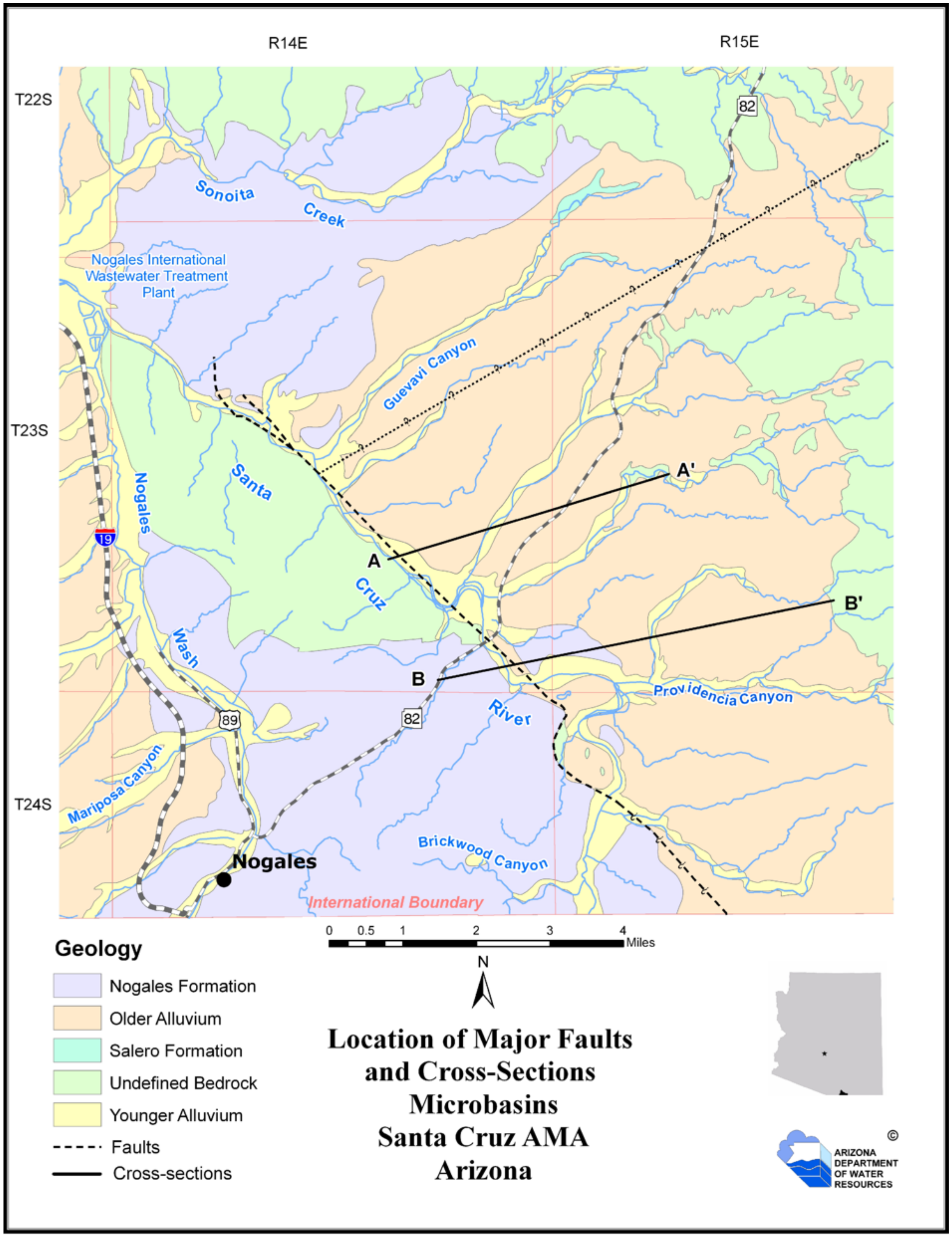

Figure 2-C. Map showing Major Faults in the Microbasin Study Area.

Chapter 3 – Hydrogeology

The most productive aquifer in the microbasin model area is the younger alluvium that lies along the course of the Santa Cruz River and its tributaries. The older alluvium and Nogales Formation generally do not yield water readily to wells and are thought to be mainly fault productive (Halpenny and Halpenny, 1991). The Salero Formation yields water reasonably well (Halpenny, 1983) but is only evident in a small portion of the model area north of Guevavi Wash. Overall, there is very little information available on the aquifers in the microbasin model area. Aquifer tests were performed at only two locations in the younger alluvium and four locations outside the younger alluvium. Aquifer test results are presented in the following discussion as well as other relevant data submitted to the Department of Water Resources.

Younger Alluvial Aquifer

The younger alluvium is the primary aquifer in the microbasin model area. It is generally comprised of unconsolidated sands and gravels with occasional lenses of silt and clay. It occurs along the course of the Santa Cruz River in pockets referred to as microbasins (Halpenny and Halpenny, 1991). The microbasins are a series of four small alluvial basins surrounded by impermeable or very low permeability formations, such as the Mount Benedict quartz monzonite or the Nogales Formation. Outcrops of Nogales Formation and/or shallow bedrock also separate the basins from each other. These constrictions are generally referred to as narrows and limit the hydraulic connection between the basins (Halpenny and Halpenny, 1991). See Figure 3-a. In upstream to downstream order, the microbasins are as follows: Buena Vista, Kino Springs, Highway 82, and Guevavi. Table 3-a provides estimates of the surface area of each microbasin.

	Buena Vista	Kino Springs	Highway 82	Guevavi
Younger Alluvium Area[1] (square miles/acres)	.84/538	1.0/640	1.06/678	1.4/896
Area expanded for Riparian[2] (square miles/acres)	.98/627	.44/282	.84/538	1.22/781
Total Area (square miles/acres)	1.82/1,165	1.44/922	2.0/1,280	2.62/1,677

Table 3-a. Estimates of Surface Area of Individual Microbasins.

[1] Area of younger alluvium considered to be of sufficient thickness to include in the model as layer one. Area is slightly smaller than map area of younger alluvium.
[2] Area includes some younger alluvium and older alluvium.

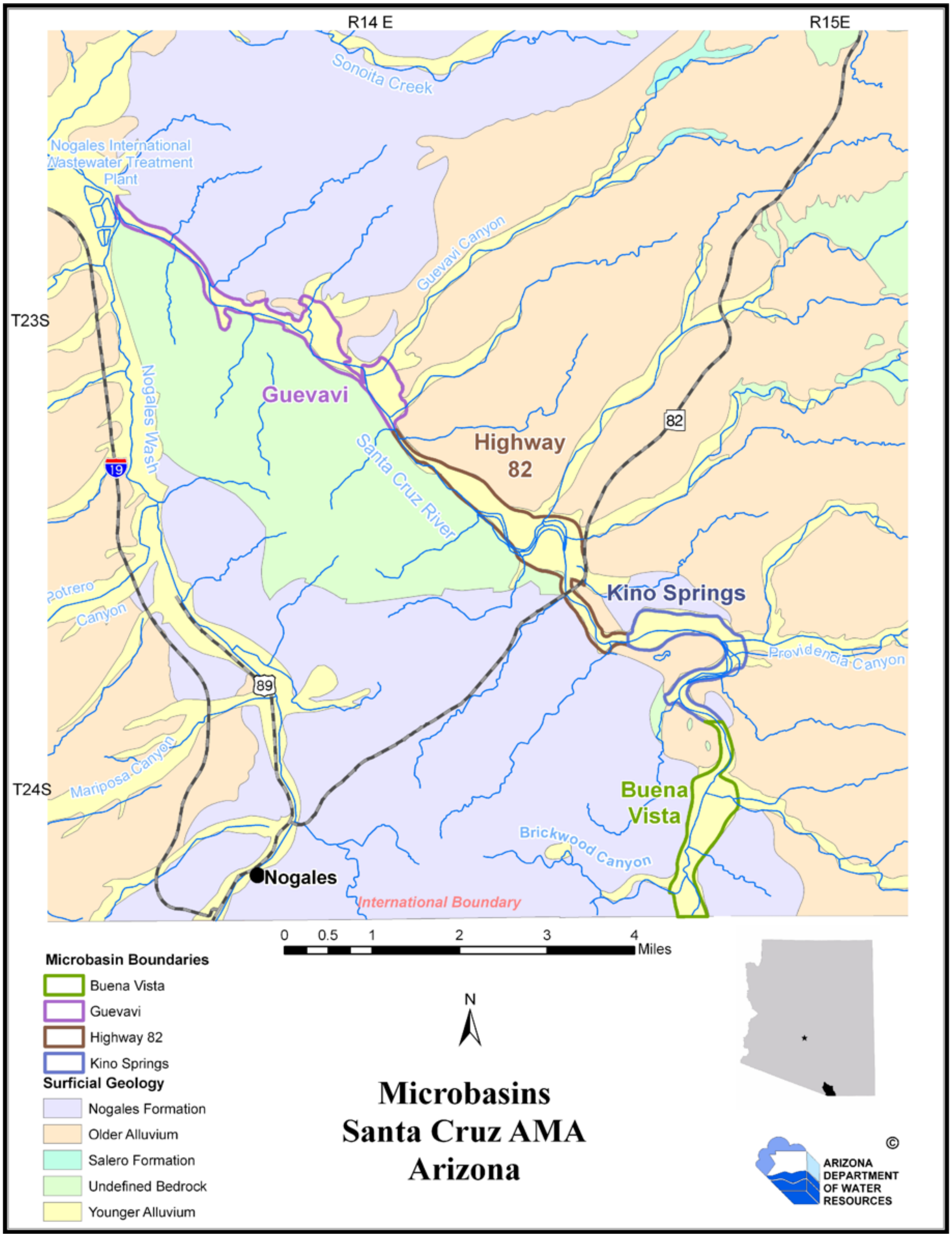

Figure 3-A. Map showing Location of Individual Microbasins.

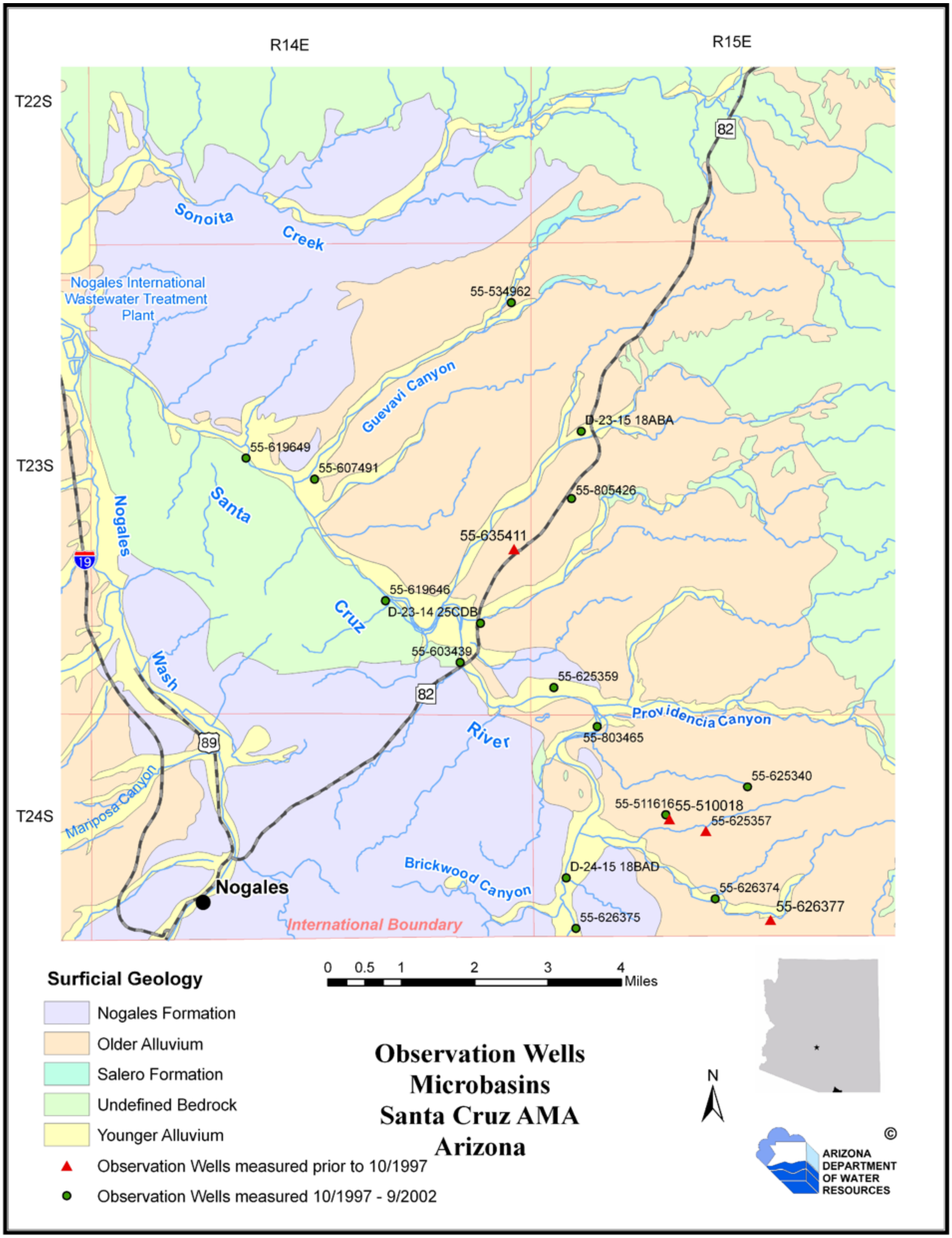

Figure 3-B. **Map showing Location of Observation Wells in the Microbasins.**

Cadastral Location	Number of Measurements (10/01/97-9/30/02)	ADWR Registration Number	UTM East (meters)	UTM North (meters)	Land Surface Elevation of Well (feet)	Well Depth[1] (feet below land surface)	Completion Date	Perforations Top (feet below land surface)	Perforations Bottom (feet below land surface)	Casing Diameter (inches)	Water Use
Younger Alluvium Wells											
D-23-14 15CCB1	41	55-607491	508765.067	3476429.965	3557						U
D-23-14 16BCC	60	55-619649	507207.079	3476921.346	3512	48	6/1/1945	18	45		S
D-23-14 25CDB	20		512332.956	3473231.849	3614						H
D-23-14 27ADD	47	55-619646	510325.362	3473753.030	3568	130	6/25/1974	20	100	16	U
D-23-14 36BCB1	17	55-603439	511964.182	3472400.207	3616	75	1/1/1910	70	75		U
D-23-15 31CAC	37	55-625359	513945.748	3471848.520	3648	80	6/18/1979	30	80	8	H
D-24-15 06AAD	58	55-803465	514897.823	3470987.834	3662	59					U
D-24-15 18BAD UNSURV	49		514318.722	3469509.317	3712						S
D-24-15 18DCB UNSURV	13	55-626375	514401.998	3466584.810	3726	93	11/22/1977	32	43	16	HS
								50	93		
Older Alluvium/Nogales Formation/Bedrock Wells											
D-23-14S01ACA	1	55-534962	513089.93	3480313.5	3990	355	4/17/1992	260	340	6	H
D-23-14 24DAC	0	55-635411	513149.540	3474895.200	3797	165	1959				H
D-23-15 18ABA UNSURV	1		514624.585	3477483.246	3880						H
D-23-15 19ABB	*5	55-805426	514415.439	3476005.233	3895	425					H
D-24-15 04DDD1 UNSURV	5	55-625340	518281.206	3469669.414	4018	264	1973	0	264	13	U
D-24-15 08ADD	0	55-625357	517305.013	3468898.115	3840	100	1/1/1962	16			
D-24-15 08ADB UNSURV	1	55-511616	516485.753	3469050.722	3840	500					U
D-24-15 08ADC UNSURV	0	55-510018	516485.899	3468958.365	3844	1000	7/11/1985	234	500	9	U
								500	1000		
D-24-15 15CDB	0	55-626377	518788.390	3466745.600	3950	74	Prior to 1912				U
D-24-15 16DBB UNSURV	*1	55-626374	517572.052	3467205.355	3875	703	6/20/1977	178	418		S
							4/25/1980	168	418		
								418	703		

Table 3-b. Table showing Observation Well Information.

*55-805426 – 2 measurements made after recently being pumped.
*55-625346 – 1 measurement made after recently being pumped.
*55-626374 – only measurement taken during well being pumped.

Construction information from the ADWR GWSI database except for lighter colored text that is from the Wells 55 database. The Wells 55 database information is supplied by the well owner and not field verified by ADWR.

<u>Water Use Codes</u>
H – Domestic
P – Public Supply
S – Stock
U - Unused

[1]Well depths may be shallower due to sediment deposition during flood events.

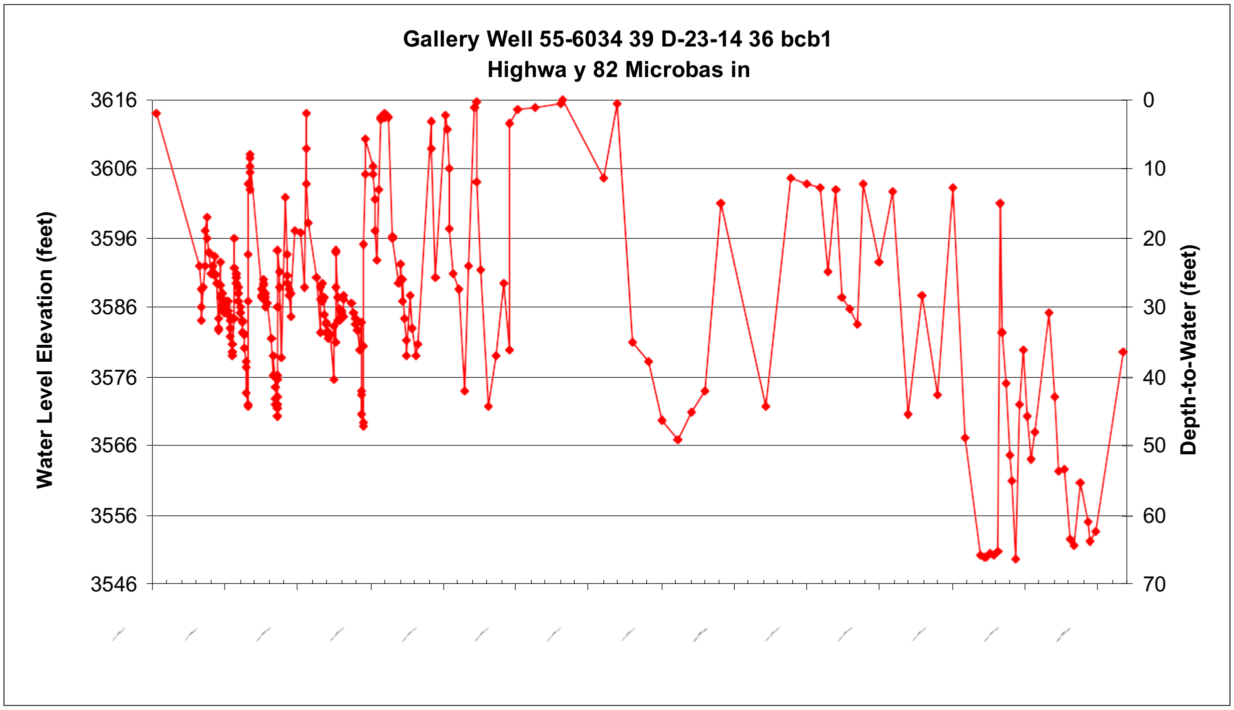

Figure 3-C. Hydrograph showing Historical Groundwater Level Fluctuations at Gallery Well 55-603439 in the Highway 82 Microbasin.

Most wells in the younger alluvium are relatively shallow ranging from 45 – 100 feet, with some extending to 150 feet into bedrock or Nogales Formation. The magnitude of the groundwater level fluctuations in the individual microbasins varies significantly. Seasonal groundwater level changes are generally less than 10 feet in the Buena Vista and Guevavi microbasins. However, with the recent addition of town City of Nogales wells (2000) in the Guevavi microbasin there is more variation. In the Kino Springs and Highway 82 microbasins groundwater levels have the greatest fluctuations. Groundwater levels in observation well D-23-14 36 bcb1 (55-603439), have fluctuated more than 50 feet in a season in response to increased summertime demand and decreased flow in the river. See Figure 3-C.

Figure 3-D illustrates the seasonal nature of the microbasin hydrologic system. Summer seasons can usually be identified as the troughs in the hydrographs. The system becomes stressed in early summer before the monsoons begin as a result of increased demands, i.e., evapotranspiration and pumpage, combined with typically little or no flow in the river during that time.

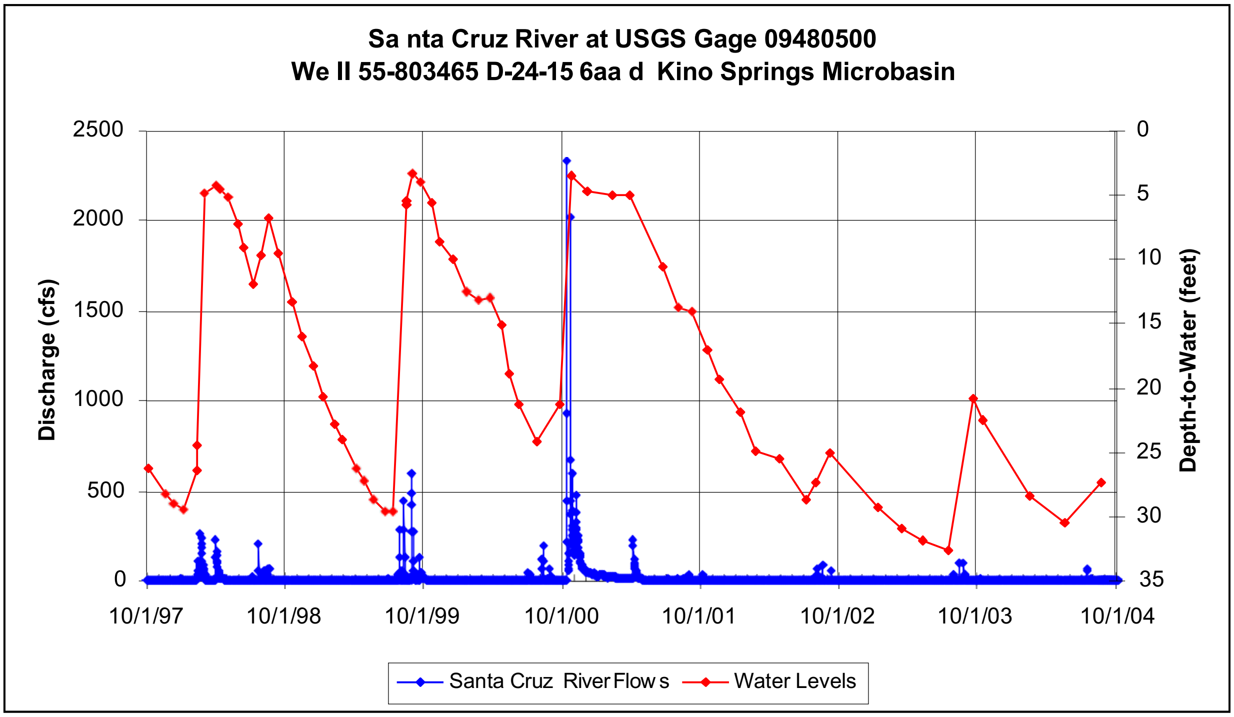

Figure 3-D. Hydrograph showing Seasonal Character of Microbasin Water Levels in the Kino Springs Microbasin and Response to Flow in the Santa Cruz River.

During times of low surface water flows, the upstream microbasin is the first to be recharged. As the storage capacity of the individual microbasin nears its maximum, more surface flow is available to the next microbasin. Surface water will flow throughout the entire reach during times of high flows because the rate and volume of flow exceeds the recharge capacity of the younger alluvium or because the upstream microbasin is already full (Putman, 1983). If there is available storage space in the aquifer, flow in the river is readily recharged as shown by Figure 3-D.

The microbasins are highly dependent upon flood flows in the river for recharge. Model results and hydrographs indicate recharge from other sources including tributaries, agricultural returns, subflow, and underflow from the older alluvium and the Nogales Formation to be minimal in the Kino Springs and Highway 82 microbasins. Direct recharge from the infiltration of precipitation on the adjacent basin fill deposits is limited due to the indurated nature of the older alluvium and Nogales Formation. Well logs on the east side of the river (D-23-15 31aad, 55-555496; D-24-15 8ada, 55-506096; and D-24-15 7d) indicate several hundred feet of granite overlying conglomerate, granite from the surface to the total depth of the well, or Nogales Formation at the land surface. These physical impediments isolate the two microbasins. Hydrographs in the Buena Vista (Figure 3-E) and Guevavi microbasins show more stable groundwater levels unlike the acute changes shown in Kino Springs and Highway 82 microbasins suggesting recharge from other sources in addition to streamflow. Buena Vista is supplied at least partially by underflow from Mexico. The Guevavi Wash acts as a discharge point for the Salero Formation (Halpenny, 1983) into the Guevavi microbasin. It is possible that each area may be supplied by water in fractures or faults as well.

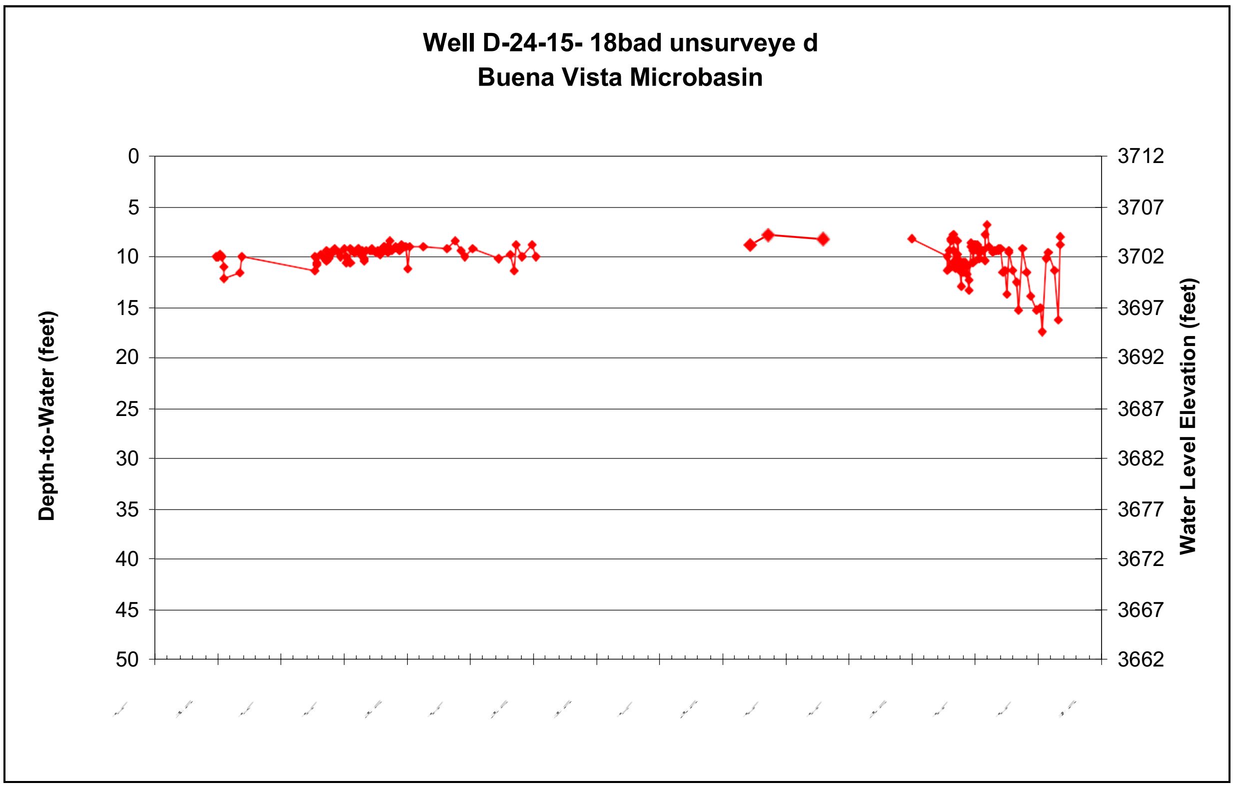

Figure 3-E. Hydrograph showing Historically Stable Water Levels in the Buena Vista Microbasin.

In contrast to the Kino Springs and Highway 82 microbasins, the Buena Vista and Guevavi microbasins are not stressed in the same capacity. In recent years water levels have declined further than any previously measured in the Guevavi microbasin. The installation of the two new City of Nogales wells in the summer of 2000 and the prolonged drought conditions are the likely cause of the groundwater level declines. Figure 3-F shows recent groundwater level measurements in a well referred to as the windmill well D-23-14 16bcc (55-619649). The current depth of the well is unknown due to sanding in of the casing during flood events (Fish, R., 2006).

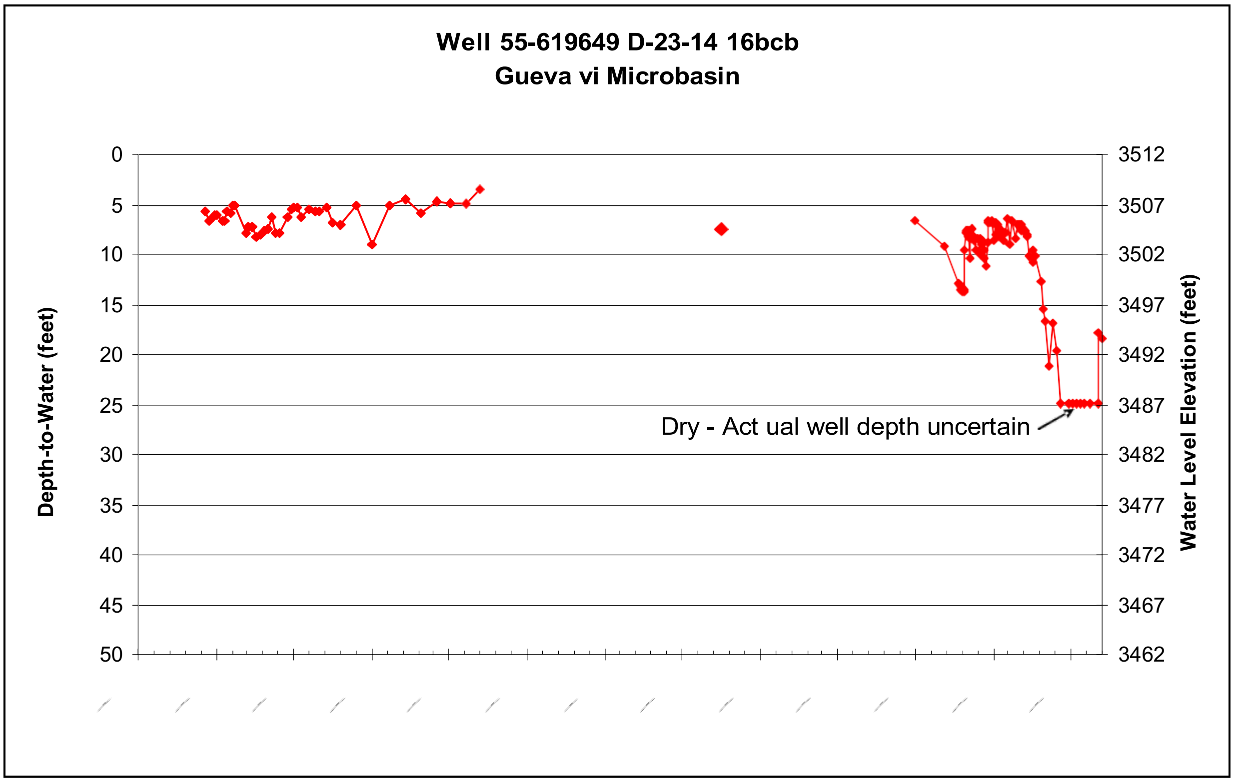

Figure 3-F. Hydrograph showing Historically Stable Water Levels and Recent Declines in the Guevavi Microbasin.

Infiltration of surface flow in each microbasin can occur rapidly if aquifer storage space is available. Figure 3-G shows the aquifer's response to the October 2000 storm event. A pressure transducer (continuous recording device) located in the Highway 82 microbasin at D-23-14 36bcb1 (55-603439) shows a water level rise of 19 feet in 24 hours. The aquifer was effectively refilled within a few days of continuous flow in the river. The younger alluvium is highly productive with transmissivities ranging from 13,400 feet^2/day to possibly 93,600 feet^2/day (100,000 - 700,000 gpd/ft) (Halpenny, 1963, and Putman, et al, 1983). However, it can only sustain high production rates for a limited time since groundwater storage is limited and recharge is intermittent.

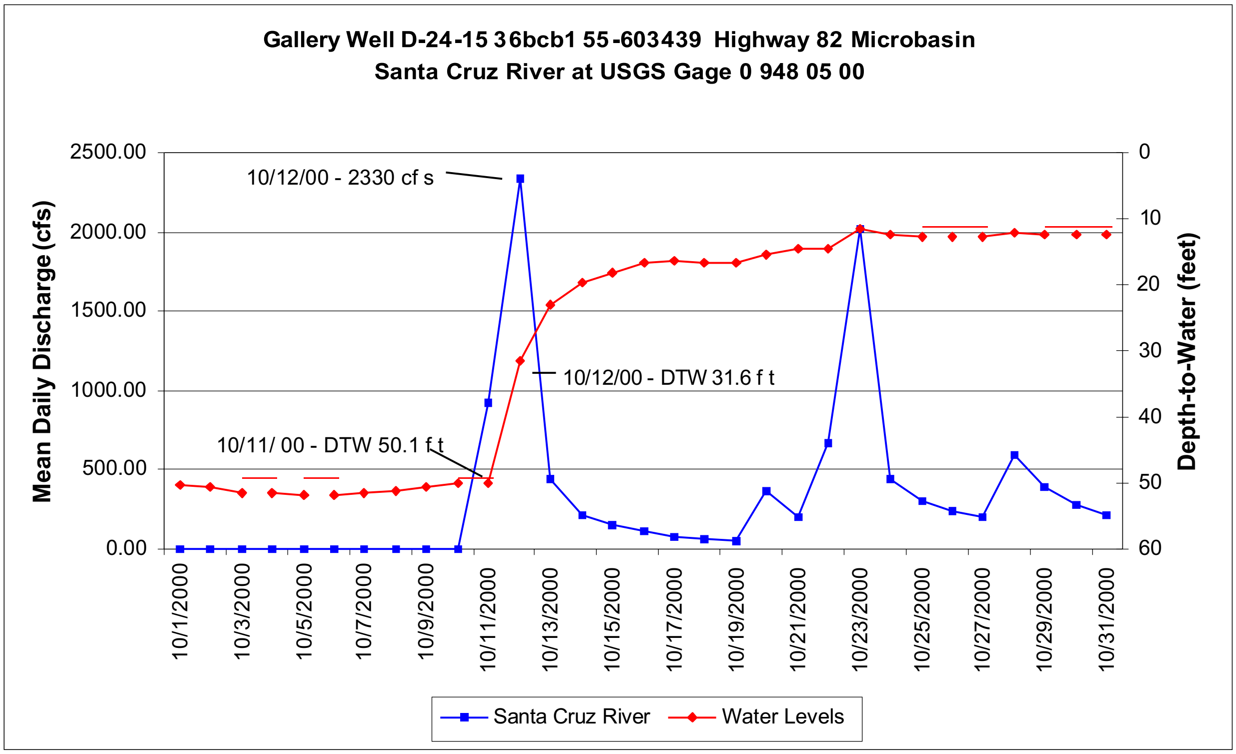

Figure 3-G. Hydrograph showingWater Level Response to Santa Cruz River Flow in the Highway 82 Microbasin.

Aquifer Tests in the Younger Alluvium

Burro Canyon Dam Site Study

Halpenny (1963) conducted an aquifer test in a well located near the Guevavi Narrows in conjunction with the study at the Burro Canyon Dam Site. See Figure 3-H for location of aquifer tests. The pumped well was 38 feet from the Santa Cruz River on the southwest side. There were five observation wells. The maximum transmissivity was estimated to be approximately 77,500 ft^2/day (580,000 gpd/ft). The transmissivity in the observation wells ranged from 43,500 ft^2/day to 80,200 ft^2/day (325,000 gpd/ft - 600,000 gpd/ft). Halpenny concluded that the "tests indicate a coefficient of transmissivity very close to the upper limit known (to the author) for alluvial sand and gravel in the southwestern United States." Four of the five observation wells exhibited a specific yield of .20 and the other well was .14. Table 3-a presents the data available from the report. Apparently there was some difficulty in conducting an acceptable test and three tests were done before a consistent data set was obtained. For more information regarding the tests, see the original report.

	Total Depth of Well (feet)	Depth to Bedrock (feet)	Depth of Hole not sanded up prior to final test (feet)	Specific Yield	Estimated Transmissivity (feet^2/day) (gpd/ft)
Well No. 4	137	86	85	.14	43,500 (325,000)
Well No. 9	101	91	38	.20	66,800 (500,000)
Well No. 10	103	93	58	.20	80,200 (600,00)
Well No. 12	92	90	72	.20	52,100 (390,000)
Well No. 13	117	91	53	.20	58,800 (440,000)

Table 3-c. Aquifer Test Data presented in the 1963 Burro Canyon Dam Site Study Report (Halpenny, 1963).

Buena Vista Ranch Development Study

Putman, et al (1983) reported on an aquifer test conducted in 1983 in conjunction with an application for an assured water supply certificate. The well was located near the International Boundary on the Buena Vista Ranch, D-24-15 18dcb, 55-626375. Although transmissivity values varied between 6,200 gpd/ft and 600,000 gpd/ft depending on the method of analysis, Putman, et al estimated the average transmissivity value to be 124,000 gpd/ft. See Table 3-b. The average discharge was 200 gallons per minute (gpm) and maximum drawdown was 27 feet. The pumped well was approximately 265 feet from the Santa Cruz River and 280 feet from the younger alluvium contact with the Nogales Formation.

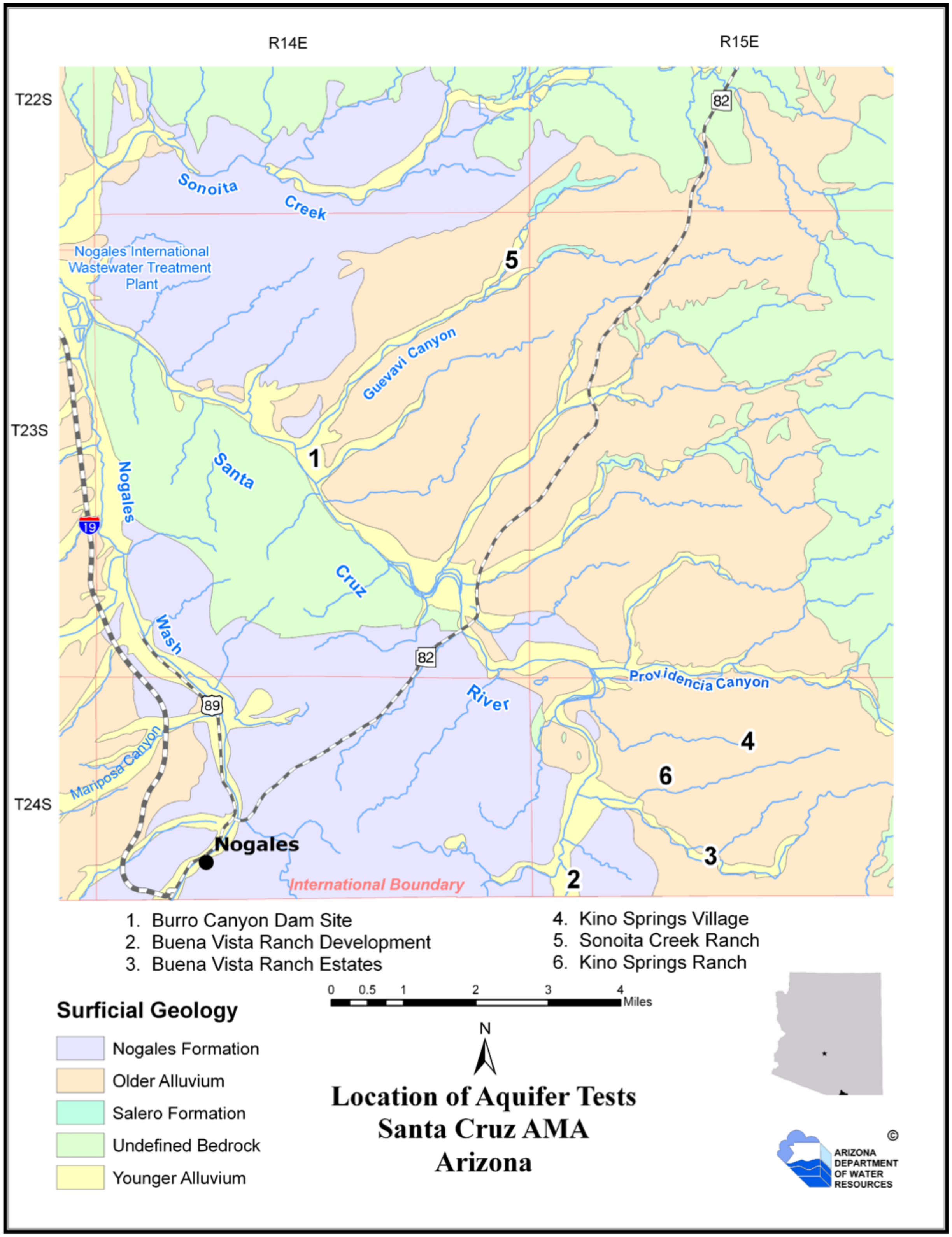

Figure 3-H. **Map showing Locations of Aquifer Tests in the Microbasins.**

	Distance from Pumping Well (feet)	Well Depth (feet)	Average Discharge (gpm)	Maximum Drawdown (feet)	Specific Yield (%)	Estimated Transmissivity Range (feet^2/day) (gpd/ft)
Observation Well #1	41.4	(1)	n/a	6.4	(1)	830 – 60,300 (6,200–51,000)
Observation Well #2	70.8	(1)	n/a	7.2	(1)	3,300–80,400 (24,500–601,500)
Pumped Well D-24-15 18dcb	n/a	93 (90 to bedrock)	200	27	.17	13,900–23,500 (104,000 – 176,000)

Table 3-d. Aquifer Test Data presented in the Buena Vista Ranch Development Study (Putman, et al, 1983).

(1) Information was not available in the report.

Older Alluvial Aquifer

The older alluvial aquifer is located between the International Boundary and Guevavi Wash and between the Santa Cruz River and the Patagonia Mountains. No older alluvium occurs west of the river. The groundwater in the older alluvium is under unconfined to confined conditions. Wells away from the river generally encounter first water in the range of 100 to 400 feet. A number of wells drilled in the older alluvium are completed in the Nogales Formation complicating identification of aquifer-specific hydraulic properties. The geologic contact between these two units is gradational (Gettings and Houser, 1997) and ambiguity in well logs further complicates analyses.

Recharge to the older alluvium is minimal. Halpenny (1963) notes "The gradient from mountain ridge to river channel is so steep, runoff in side washes is extremely rapid all seasons of the year. Thus, all of the side washes have dry channels except for brief periods during and following a rainstorm." Groundwater movement in the older alluvium is probably aligned with faults and fractures where secondary porosity is limited.

The older alluvium is of a slightly different character north of the northeast – southwest trending fault aligned with Guevavi Wash. Very few well logs are available for the area. Halpenny

(1983) reported the thickness of this unit ranges from a few inches along some of the washes to about 200 feet under the mesas. The older alluvium is partially indurated and forms steep cliffs along the borders of some of the washes. During Halpenny's investigation he determined that the older alluvium in the area was generally above the water table and was not found to be water bearing at any of the holes drilled during his investigation.

Aquifer Test in the Older Alluvium

The author is aware of only one aquifer test conducted in what may be mostly older alluvium. This test was conducted in 1977 in a well located in D-24-15 16bdd, 55-626374 and was reported by Manera and Associates, Inc. (1980) in the Buena Vista Ranch Estates study. The total depth of the well was 418 feet with the upper 375 feet appearing to be older alluvium. The remaining 48 feet is most likely Nogales Formation.

Well Depth (feet)	Perforated Interval (feet)	Average Discharge (gpm)	Maximum Drawdown (feet)	Trans-missivity $feet^2/day$ (gpd/ft)	Storage Coefficient	Inferred Hydraulic Conductivity (feet/day)
418	168-418	82-100	135	75 (560)	1.4e-3	0.3

Table 3-e. Aquifer Test Data presented in the Buena Vista Ranch Estates study (Manera, 1980).

Nogales Formation

Unfortunately, little data are available to characterize the Nogales Formation. Halpenny had hoped to learn that the Nogales Formation would yield groundwater to wells at the beginning of his investigation for the Burro Canyon Dam Site (1963). As of July 1963 no wells along the Santa Cruz River were known (to Mr. Halpenny) to produce water from the Nogales Formation other than a few stock wells at the edge of the valley. They apparently obtained a few gallons per minute from the upper 20 to 30 feet of the formation. Halpenny reported that the water bearing character of the Nogales Formation was tested during July and August 1963 by core drilling at Granger Well No.7A. The site is in the Maria Santisima del Carmen Grant in what is equivalent to D-24-15 7d. Total depth of the hole was 786 feet in the Nogales Formation, from the land surface to the total depth. Two tests were performed in which packers were set and water was injected into the well under high pressure. During both of these tests no measurable quantity of water could be forced into the formation, indicating it was too tight to yield water to a well.

Aquifer Tests in the Nogales Formation

Kino Springs Village

Halpenny (1981) conducted aquifer tests on two wells in Kino Springs Village in September 1981; Well No. 19, D-24-15 4ddd2 (55-625346) and Well No. 15, D-24-15 10acb (55-625341). According to the Department's Groundwater Site Inventory (GWSI) database, Well No. 15 is approximately 472 feet deep with perforations between 125 and 307 feet. There is no log available for the well. Halpenny reported as follows "During the test the discharge was extremely erratic. Water would gush out for a few seconds at about 10 gpm and then would decrease to less than one gpm. The water would rise slightly, a slug of muddy water would issue, and then the discharge would increase to about 10 gpm for another few seconds. The cycle would then repeat." In Halpenny's opinion the sustainable yield from this well was no more than one gpm.

The aquifer test on Well No. 19 was also problematic. Erratic water levels and discharges were endemic to the test as well as a long recovery period. The total depth of the well is 655 feet. The well was only pumped for approximately one hour and the discharge rate started at 50 gpm but quickly dropped to 27 gpm. After the pump was shut off the water level only rose 0.1 feet in 3 hours. Halpenny estimated the sustainable discharge of the well to be only 25 to 26 gpm. It was also noted that the water level in the nearby observation well No. 19A, D-24-15 4ddd (55-625340) appeared to be unaffected by on-off cycles of Well No. 19.

In November 1980, the well previously discussed, D-24-15 16bdd (55-626374), as an older alluvium aquifer test well was deepened from 418 feet to 702 feet and Manera and Associates, Inc. conducted another aquifer test. The well is perforated in both older alluvium and Nogales Formation. Manera reports a composite hydraulic conductivity value of 0.5 feet per day. The production from both older alluvium and Nogales Formation as well as the recovery data are indicative of the presence of fractures and/or bedding planes (Putman, et al, 1983).

Well depth (feet)	**Perforated interval (feet)**	**Average Discharge (gpm)**	**Maximum Drawdown (feet)**	**Trans-missivity feet^2 /day (gpd/ft)**	**Storage Coefficient**	**Inferred K (feet/day)**
702	168-702	188	150	279 (2086) [1] 239 (1785) [2]	2.5e-6 1.0e-6	0.5 0.4

Table 3-f. Results of Aquifer Test at D-24-15 16bdd, 55-626374 (Manera and Associates, Inc., 1980).

[1]Theis drawdown analysis (Theis, 1935).
[2]Papadopulos-Cooper drawdown analysis (Papadopulos and Cooper, 1967).

Salero Formation

The Salero Formation is the principal water-bearing formation in the area between Sonoita Creek and Guevavi Wash. A study conducted by Halpenny (1983) indicated the conglomerate to be well cemented in areas but that a prolific water-producing zone was encountered in a sand/gravel unit. Groundwater contour lines indicate the movement of groundwater is generally southwestward, perpendicular to the Patagonia Mountains and the Santa Cruz River. The groundwater is discharged into the Santa Cruz River inner valley in the vicinity of Guevavi Wash.

Aquifer test in the Salero Formation

Sonoita Creek Ranch

Halpenny (1983) conducted aquifer tests on three wells in the northeast corner of the modeling area known as Sonoita Creek Ranch. These wells are all located north of the inferred southwest-northeast trending fault (Simons, 1974) aligned with Guevavi Canyon and are all completed in Salero Formation . The estimated storage coefficient was .1 to .15 based on responsiveness of a nearby stock well.

Cadastral Location	Total Depth (feet)	Average Discharge (gpm)	Drawdown (feet)	Specific Capacity (gpm/ft of drawdown)	Estimated Transmissivity (feet^2/day) (gpd/ft)
D-23-15 5add	387	74.1	31.1	2.4	2,000 (15,000)
D-22-15 31cad	285	88.7	57.3	1.6	740 (5,500)
D-23-14 1cad	385	40.3	21.5	1.9	2,000 (15,000)

Table 3-g. Aquifer Test Data reported in the Sonoita Creek Ranch Study (Halpenny, 1983).

Aquifer Test in Bedrock

Kino Springs Ranch

Halpenny and Halpenny (1985) conducted an aquifer test on a well located at D-24-15 8adc, 55-510018, in August 1985. The well was 1,000 feet deep. Halpenny and Halpenny determined the upper 190 feet to be the older alluvium unit and the remaining 810 feet as granodiorite. They concluded the older alluvium acts as the aquitard and the granodiorite as the aquifer. Tests indicated that nearly all of the water was entering the well bore between depths of 180 and about 355 feet, and that little or no water was produced below a depth of 355 feet. A Theis drawdown analysis calculated a transmissivity value of 848 gpd/ft inferring a hydraulic conductivity value of less than 1.0 foot per day. The storage coefficient was calculated to be 1.1e-4. Artesian conditions were noted in both the pumped well and the observation well, D-24-15 8adb (55-511616), which was located approximately 500 feet north of the pumped well.

Chapter 4 - Groundwater Flow System

Groundwater Development – Historical Use

Groundwater is pumped in the microbasins for a variety of purposes including agriculture and domestic use but the principal use is municipal. The Santa Cruz River microbasins have been supplying the City of Nogales with water since at least 1911 when the City contracted to build a pumping plant, including a well and infiltration gallery on the banks of the river approximately five miles north of the International Boundary (Carollo, 1964). This is currently the location of the State Highway 82 Bridge. A second well was dug in 1920. An extended drought in 1962-1963 caused the infiltration gallery to go dry and prompted the City to install more wells near the river channel. By 1974 the City of Nogales had installed three wells near the infiltration gallery in the floodplain to augment the domestic water supply. The Santa Cruz River younger alluvial aquifer was the City's sole source of water until the Potrero Wellfield (west of Nogales) was established in 1970 (Halpenny, 1995). The City now uses both the PotreroWellfield and the Santa Cruz River younger alluvial aquifer for supply.

Conceptual Model of Groundwater Flow System

General Character

The rate and direction of groundwater movement in the regional aquifers are controlled by the hydraulic gradient and the permeability of the aquifers. The older alluvial aquifer and the Nogales Formation aquifer for the purposes of this study are limited to the area between the Santa Cruz River and the Patagonia Mountains on the east and between the International Border and Guevavi Wash to the north. As discussed in the previous chapter, flow in the older alluvium and Nogales Formation is likely fault controlled. Groundwater level contour maps (Nelson and Erwin, 2000; Murphy and Hedley, 1982) show flow directions towards the valley axis. Hardrock

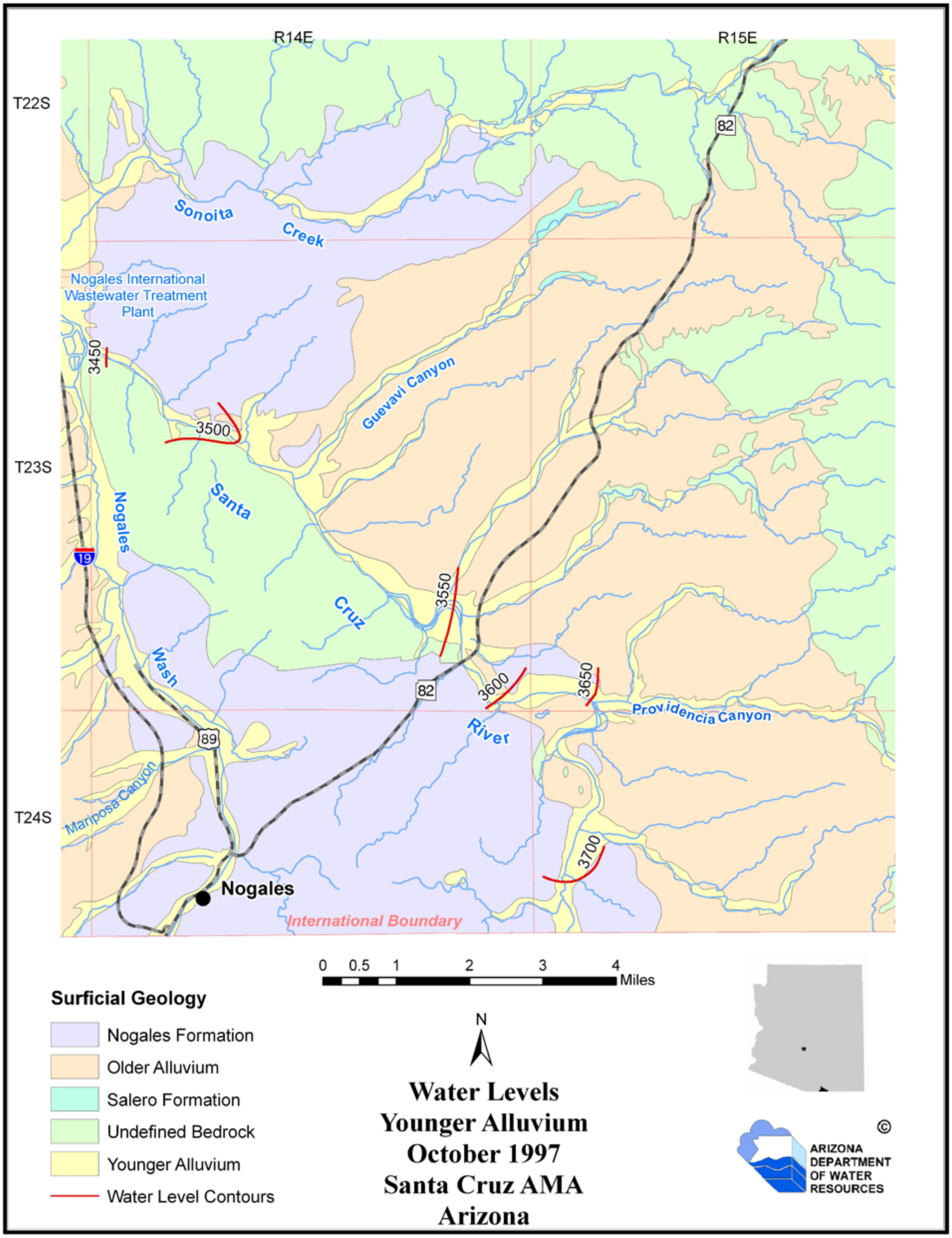

Figure 4-A. Map showing Water Levels in the Younger Alluvium at the beginning of the Study Period – October 1997.

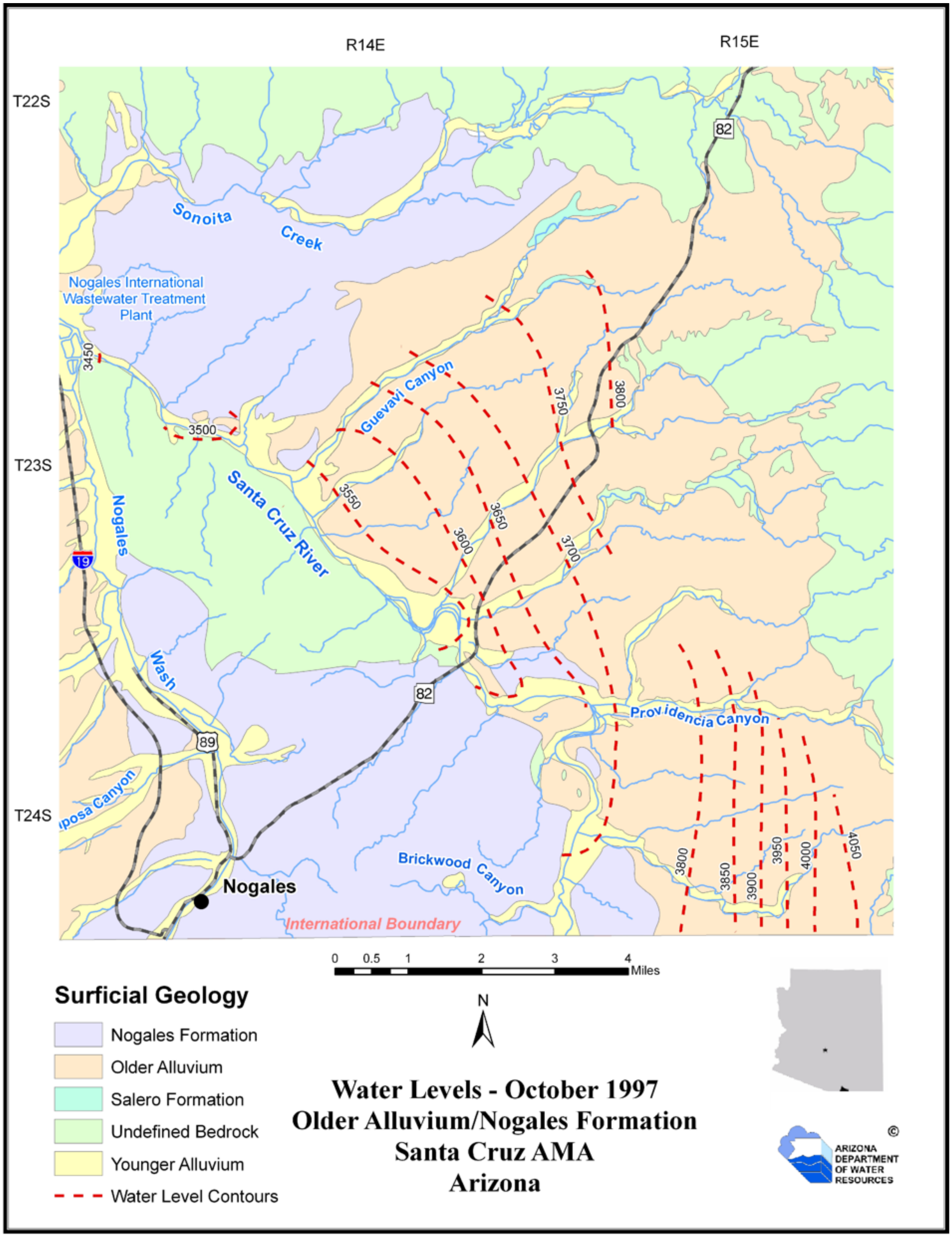

Figure 4-B. Map showing Composite Water Levels in the Older Alluvium and Nogales Formation at the beginning of the Study Period – October 1997.

and/or Nogales Formation outcrops may alter this general pattern near the river. See Figures 4-A and 4-B. In the younger alluvium groundwater generally flows parallel to the course of the Santa Cruz River.

Inflows

Recharge

Underflow

Average annual groundwater underflow from Mexico at the International Boundary into the United States was estimated at approximately 500 acre-feet per year using a simple Darcy Strip analysis with the following equation:

$$Q = W \bullet K \bullet d \bullet \frac{dh}{dx}$$

where Q = the flow from Mexico
W = the width of the younger alluvium
K = hydraulic conductivity based on aquifer test by Putman, et al
d = average saturated thickness of the younger alluvium
dh/dx = gradient based on water levels

The volume was varied seasonally based on a change in gradient and saturated thickness as measured during monthly water level measurements. Other estimates of underflow were made by Putman, et al (1983) - 577 acre-feet/year and Halpenny (1963) - 410 acre-feet/year. Underflow into the model area from Mexico via the older alluvium and Nogales Formation was considered negligible based on an analysis of groundwater flow directions.

Streamflow Infiltration

Estimating annual streamflow infiltration from surface water flow for the microbasin model without an outflow gage is very difficult. The magnitude and duration of the flows as well antecedent conditions are integral to the estimate. The volume of recharge fluctuates from year to year in accordance with groundwater levels and availability of surface water. When water levels are low and there is storage space in the aquifer, infiltration rates can be quite high. When the water table rises, the infiltration rate decreases because it is limited by the rate at which groundwater moves laterally from the stream channel to the edges of the valley. Halpenny (1963) estimated a stream infiltration rate to be approximately 1.5 acre-feet per day per acre of wetted stream channel when the river is flowing and when the water table is at a lower stage. Osterkamp (1973) estimated average annual recharge to be approximately 400 – 600 acre-feet per mile along the Santa Cruz River in the microbasin area. This equates to approximately 5,700 – 8,600 acre-feet per year. Generalizations relating the volume or rate of recharge to flow at the stream gage generally result in exaggerated estimates.

Mountain Front Recharge

In general, mountain front recharge occurs primarily from infiltration along small stream channels and from subsurface seepage of water from consolidated rocks. In the mountains ephemeral streams lose small amounts through joints and cracks in the consolidated rocks. The water moves toward the valley and seeps into the sand, gravel, and silt that fill the valley. This is evidenced by groundwater flow contours. Typically mountain front recharge rates are normalized throughout the year even though the recharge likely occurs in pulses. Osterkamp (1973) estimated the long-term average rate at 3,900 acre-feet per year, which is approximately 200-400 acre-feet per year per mile of mountain front.

Halpenny (1963) reported that it was unlikely that precipitation directly contributed substantially to groundwater recharge. He noted that runoff in side washes is extremely rapid during all seasons of the year and that all of the side washes in the microbasin model area have dry channels except for brief periods during and following a precipitation event. The gradient from the mountain ridge to the river channel is steep, approximately 500 feet per mile from the mountains to the Santa Cruz River channel. The conglomerates or surface exposure of older alluvium and Nogales Formation are relatively impermeable. Harshbarger (1979) noted that precipitation contributes runoff from the mountain slopes in the microbasin model area, but the runoff generally does not enter the subsurface until the streams traverse areas underlain by permeable alluvial materials. Precipitation would likely run off as sheet flow or tributary flow. Tributary runoff (based on estimates by Mooseburner (1970) was considered to be a part, approximately 60%, of Osterkamp's (1973) mountain front estimate of 3,900 acre-feet per year. The remaining 40% was applied at the base of the mountains as mountain front recharge. See Figure 4-C.

Recharge cells were spread evenly (approximately one-half mile wide) across the eastern model boundary on the western side of the Patagonia Mountains. A slightly higher recharge rate was applied to the cells in the northeast corner of the model area at the headwaters of Guevavi Wash based an estimate of 400-800 acre-feet per year from a study at Sonoita Creek Ranch (Halpenny, 1983).

Recharge from Precipitation on the Valley Floor

Halpenny (1963) noted there was no evidence indicating groundwater recharge from precipitation falling directly on the land surface was of hydrologic importance in the southwestern United States. Recharge from precipitation falling directly on the desert floor is considered negligible on the basis of soil-moisture tests before and after storms. This is because of a deficiency in soil moisture due to an evaporation potential of about 91 inches per year in Nogales (WRCC, 2005), use by native desert plants, and relatively impermeable caliche zones of calcium carbonate cementation that are commonly present.

Incidental Recharge from Agriculture

The 1994–1996 irrigation efficiency in the microbasins was approximately 50 percent according to a study conducted by Nelson (1998). Irrigation efficiency is a measure of the overall effectiveness of water application during a crop season. Incidental recharge, the difference between the volume of water pumped and applied to crops and the irrigation requirement, is a small part of the overall water budget in this area and does not contribute much to the overall supply as seen below in Table 4-a. Incidental recharge from agriculture was not included in the model.

	1997	1998	1999	2000	2001	2002
Total Agricultural Pumpage[1]	201	358	370	290	210	137
Incidental Recharge at 50% Efficiency	100	179	185	145	105	68
Incidental Recharge at 80% Efficiency – assigned efficiency for Third Management Plan	40	72	74	58	42	27

Table 4-a. Estimated Agricultural Recharge in the Microbasins (acre-feet per calendar year).

[1]Data from Registry of Groundwater Rights, ADWR 1997 - 2002

Outflows

Pumpage

Municipal and Domestic

Municipal use accounts for the majority (85% - 96%) of the groundwater pumpage in the study area both historically and during the study period. See Figures 4-C, 4-D, and 4-E. Municipal pumpage by the City of Nogales accounts for the majority (82% - 92%) of the total groundwater pumpage. Annual groundwater pumpage data were obtained from the ADWR Registry of Groundwater Reports (ROGR) database and monthly pumpage records were provided by the City of Nogales. Nearly all of the groundwater pumpage occurs within the younger alluvium. The City has a computerized system of pumping that efficiently manages the aquifer. A small amount (approximately 20 acre-feet per year) is withdrawn from the older alluvium and Nogales Formation by the City of Nogales at the Kino Springs Village. There were approximately 200 exempt wells (wells that may legally pump no more than 35 gpm). Exempt wells are primarily used for domestic and stock purposes and represent a relatively small proportion of the overall pumpage, less than one percent. Exempt well pumpage was estimated to be about 100 acre-feet per year and was not included in the model. The City of Nogales staggers well pumpage near the Santa Cruz River.

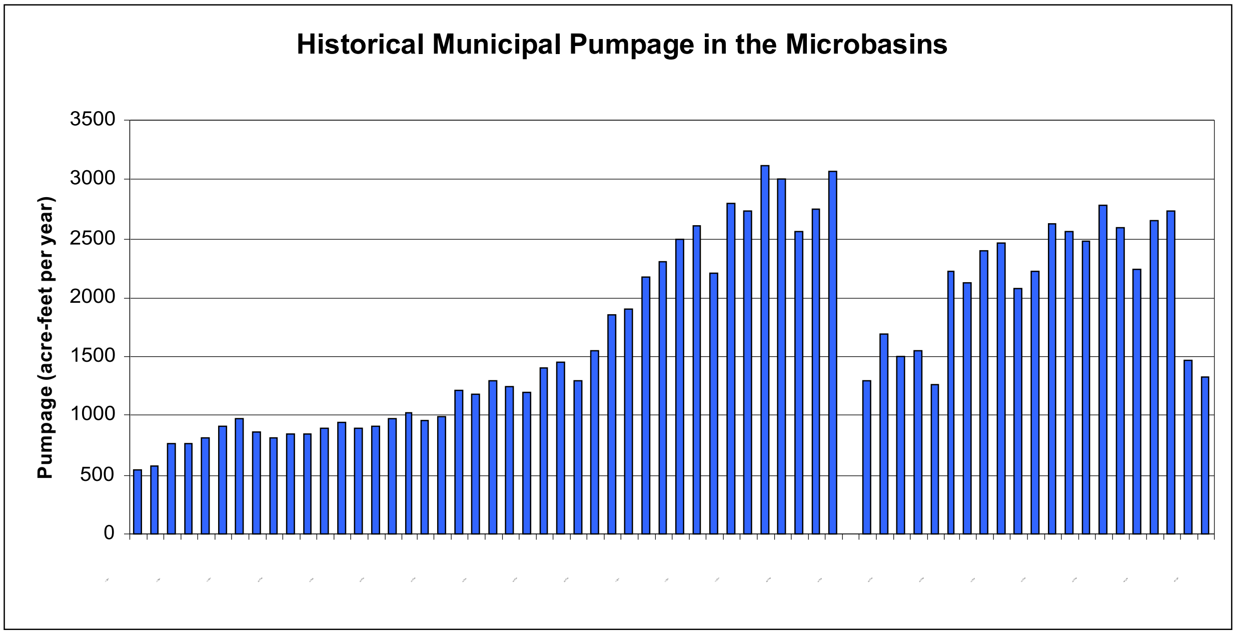

Figure 4-C. Historical Pumpage by the City of Nogales the Microbasins.

Data Sources for Figure 4-C.:
1941 - 1962 Carollo, 1964
1963 - 1975 Putman, et al, 1983. Estimated from graphs.
1976 - 1982 Putman, et al, 1983. Tabular information.
1984 - 2004 ADWR ROGR Database.

	1997	1998	1999	2000	2001	2002
City of Nogales	2,496	2,800	2,611	2,249	2,676	2,965
Small Municipal Providers[1]	81	93	107	95	104	114
Agricultural and Other	449	374	398	299	119	171
Total	3,026	3,267	3,116	2,643	2,904	3,250

Table 4-b. Reported Groundwater Pumpage in the Microbasins 1997-2002 (acre-feet per calendar year).

[1] By definition small municipal providers supply less than 250 acre-feet per year for non-irrigation uses (ADWR, 1999).

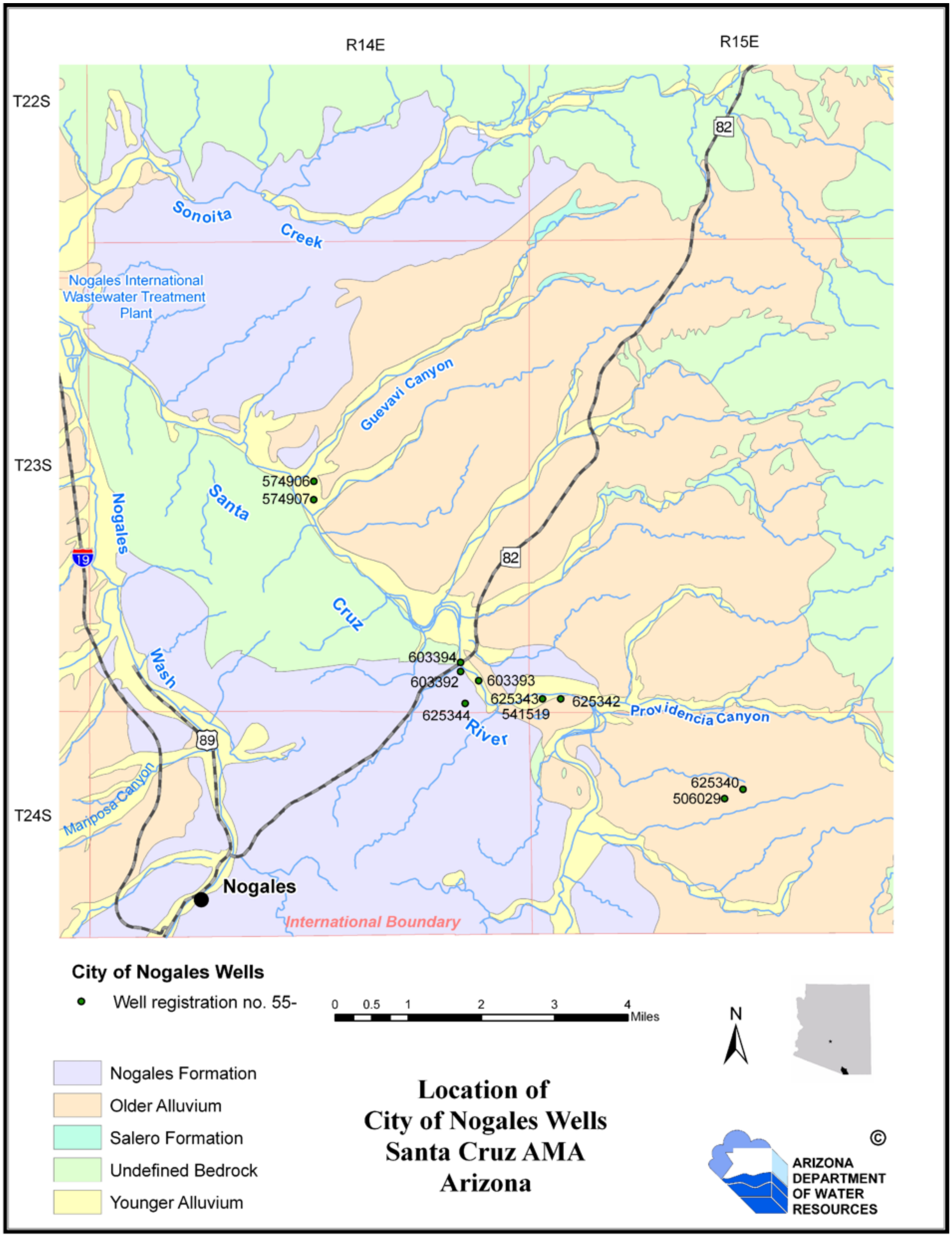

Figure 4-D. **Map showing Location of the City of Nogales Wells.**

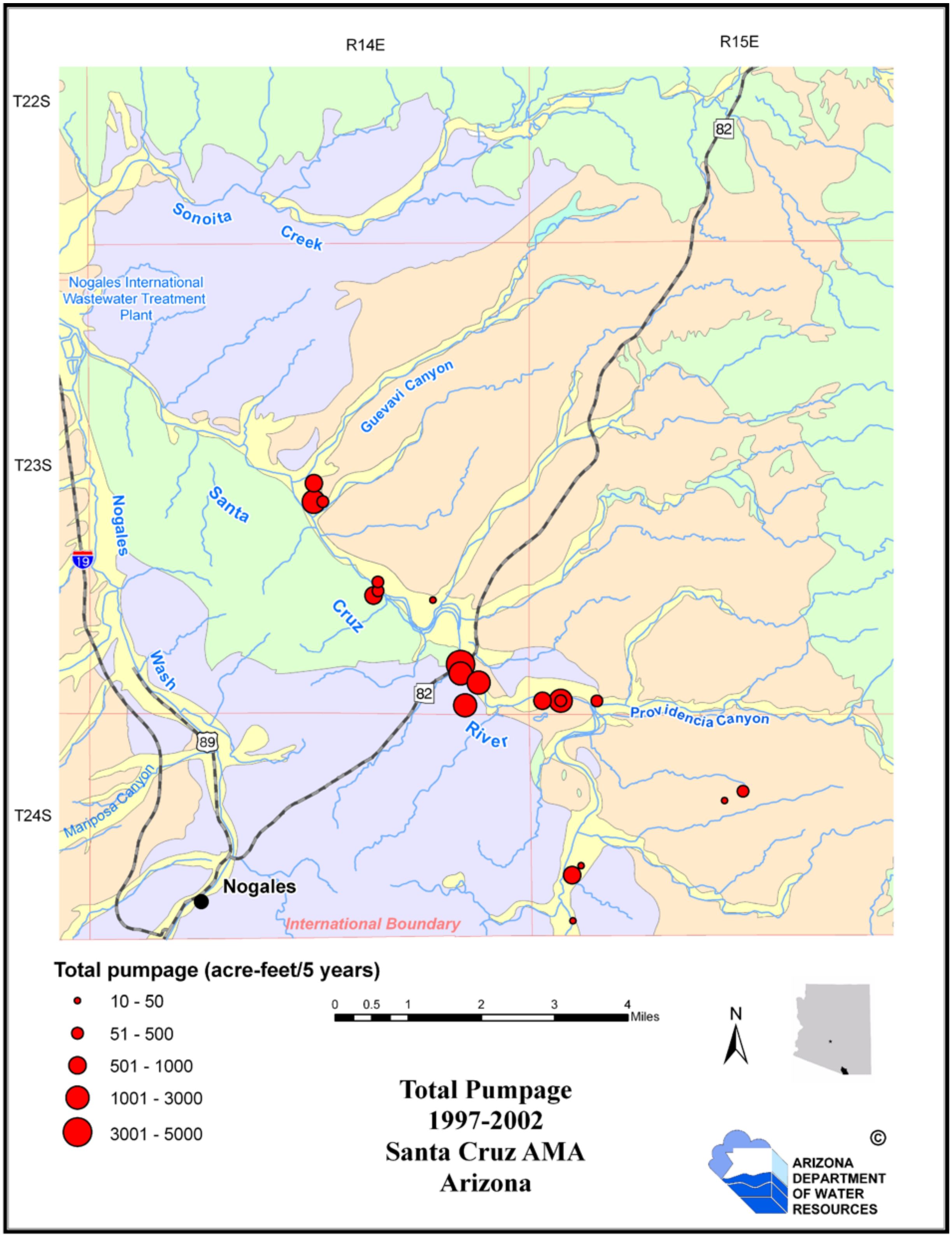

Figure 4-E. **Map showing Total Pumpage from Non-Exempt Wells 1997-2002.**

Agriculture

Only about 115 acres are certificated or are legally allowed to irrigate in the model area. ADWR annual reporting requirements do not call for the owner to report the specific number of acres irrigated. They are only required to report the pumpage. It was estimated that most irrigation was associated with permanent pasture, sorghum, oats, winter mix and hay crops based on field reconnaissance. Summer irrigation comprises approximately two-thirds of the annual usage and with the remaining one-third occurring in the winter months (Nelson, 1998).

Evapotranspiration

Riparian vegetation consumes a large amount of water along the floodplain of the Santa Cruz River. The Arizona Department of Water Resources conducted a study of riparian water use to provide hydrologic data for the groundwater model and technical support for the Santa Cruz AMA (Masek, 1996). Riparian systems were assessed from the International Boundary to Arivaca Junction for the years 1954, 1973 and 1995. Annual water consumption estimates were based on aerial photography, field estimates of density and species type, and published water use figures for each species. Consumptive use was generated by incorporating local climatological data into the Blaney-Criddle Formula (Blaney and Criddle, 1950). For more information on methodology see Masek, 1996. Seven vegetation classes were identified in the microbasin model area as shown in Table 4-c. Monthly phreatophyte use was calculated by determining the annual water use per model cell and proportioning the monthly consumptive use for that particular vegetative type as shown in Table 4-d (Gatewood, et al, 1950).

Vegetation Class	Water Use (feet per year)
Mature Cottonwood	6.1
High Density Cottonwood/Willow	6.1
Medium Density Cottonwood/Willow	3.66
Low Density Cottonwood/Willow	1.83
High Density Mesquite	3.36
Medium Density Mesquite	2.02
Low Density Mesquite	1.01

Table 4-c. Vegetation Classes and Consumptive Use Estimates for the Santa Cruz AMA Riparian Community as identified by Masek, 1996.

Month	Mesquite %	Cottonwood and Willow %
January	0	0
February	0	0
March	0	0
April	0	6.3
May	9.6	22.5
June	24.3	23.3
July	27.1	18.2
August	23.4	16.5
September	12.9	9.4
October	3.1	2.8
November	0	1.0
December	0	0

Table 4-d. Monthly Percentage of Annual Phreatophyte Use as defined by Gatewood, et al, 1950 and Masek, 1996.

Underflow at the NIWTP

Groundwater leaving the microbasin model area as underflow in the younger alluvium was estimated using a Darcy Strip analysis. This estimate was varied seasonally based on a change in gradient and saturated thickness according to monthly water level measurements to the north. An estimate of approximately 1,000 acre-feet per year was calculated. A previous estimate of 570 acre-feet per year at Eagan Narrows was reported by Halpenny (1963). Underflow via the older alluvium and Nogales Formation was considered negligible. Simons (1974) does not report older alluvium in the area known as Eagan Narrows.

Chapter 5 - Surface Water System

Watershed Description

The headwaters of the Santa Cruz River originate in the San Raphael Valley in southeastern Arizona between the Patagonia Mountains and Huachuca Mountains. The river flows south into Mexico for approximately 19 miles where it loops westward around the San Antonio Mountains then turns back north and crosses into the United States approximately 5 miles east of the City of Nogales. The river runs north-northwest through the model area for about 14.3 miles. The river exits the model area near its confluence with Nogales Wash and near the NIWTP. The river elevation at the International Boundary is 3,716 feet (msl). The elevation at the northern model boundary is approximately 3,456 feet (msl). The average channel gradient is approximately 20 feet per mile. The river drains 533 square miles at USGS gage 0904500 located approximately .75 miles north of the International Boundary, with the majority of the area, 388 square miles (ADWR, 1996) being in Mexico. The stretch of the river in the microbasin model drains approximately 110 square miles.

Data Collection

Surface water flow into the microbasins is measured at the U.S. Geological Survey Gage 09480500, Santa Cruz River near Nogales, Arizona located 0.8 miles downstream of the International Boundary. Daily streamflow data are available beginning in 1913 but data is partially missing between 1913 and 1936. The record is continuous from 1936 to present. Surface water was also measured monthly (1997-2002) at four other sites along the Santa Cruz River in the microbasin area by ADWR staff (Nelson and Erwin, 2001). These specific measurements were only snapshots in time and are not likely representative of average flows for months, weeks, or even days. The likelihood of the measurements being representative of an average flow is lower as time periods increase and is lower during periods of runoff, especially during the summer monsoon season. However, the measurements provided preliminary calibration estimates for the groundwater model. It should be noted that on several occasions the

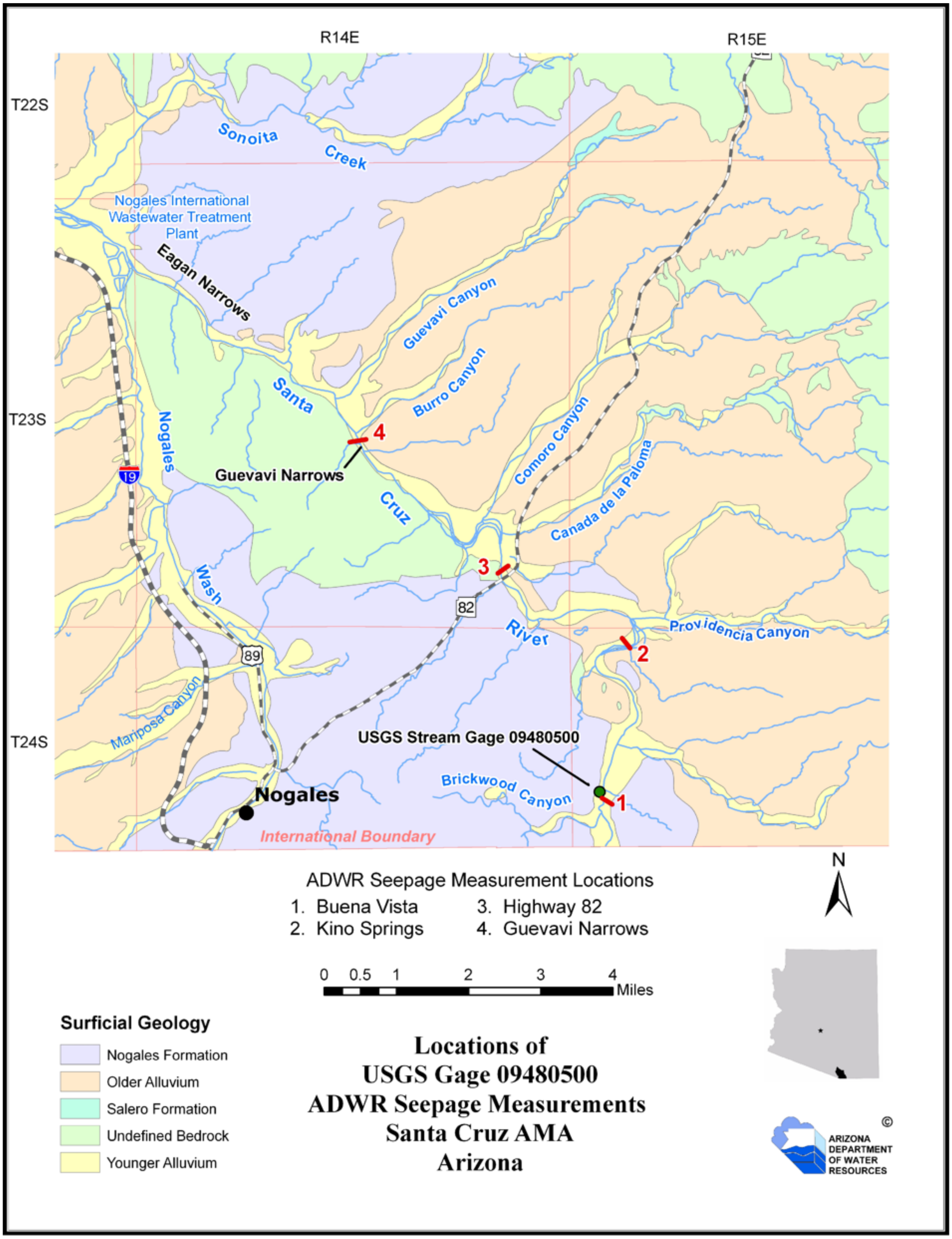

Figure 5-A. **Map showing Location of Santa Cruz River, Tributaries, USGS Gage 09480500 and ADWR Seepage Measurement Locations.**

U.S. Geological Survey gage daily average flows and the ADWR field measurement were in disagreement. Both sources were checked (i.e., ADWR field sheets and U.S. Geological Survey hourly measurements). No explanation is available and the data are considered anomalous. The daily average U.S. Geological Survey flows as reported on the U.S. Geological Survey website (http://waterdata.usgs.gov/az/nwis/sw) were analyzed to provide input to the groundwater flow model Stream-Routing package.

Character of Flow

Flow in the Santa Cruz River is ephemeral to intermittent. Figures 5-B, 5-C and 5-D illustrate the monthly and annual variability as well as the seasonal character of flows throughout the year. Figure 5-F shows the daily mean flows for the study period. Streamflow downstream of the U.S. Geological Survey gage is the result of a combination of runoff past the gage, tributary inflows, and subflow or groundwater forced to the surface at bedrock constrictions. The flow duration table, Table 5-a, is typical of highly variable stream whose flow is mostly from direct runoff and has a minimal amount of bank storage (Putman, 1983). Seasonal discharge on the Santa Cruz River is related to climatic variability. Precipitation in southern Arizona has distinct peaks in summer and winter. Averages of monthly discharge for the Santa Cruz River at Nogales indicate that runoff occurs mainly from December through February and July through October. Variability in monthly streamflow is high, and coefficients of variation range from 1 to 4.3. See Figure 5-E.

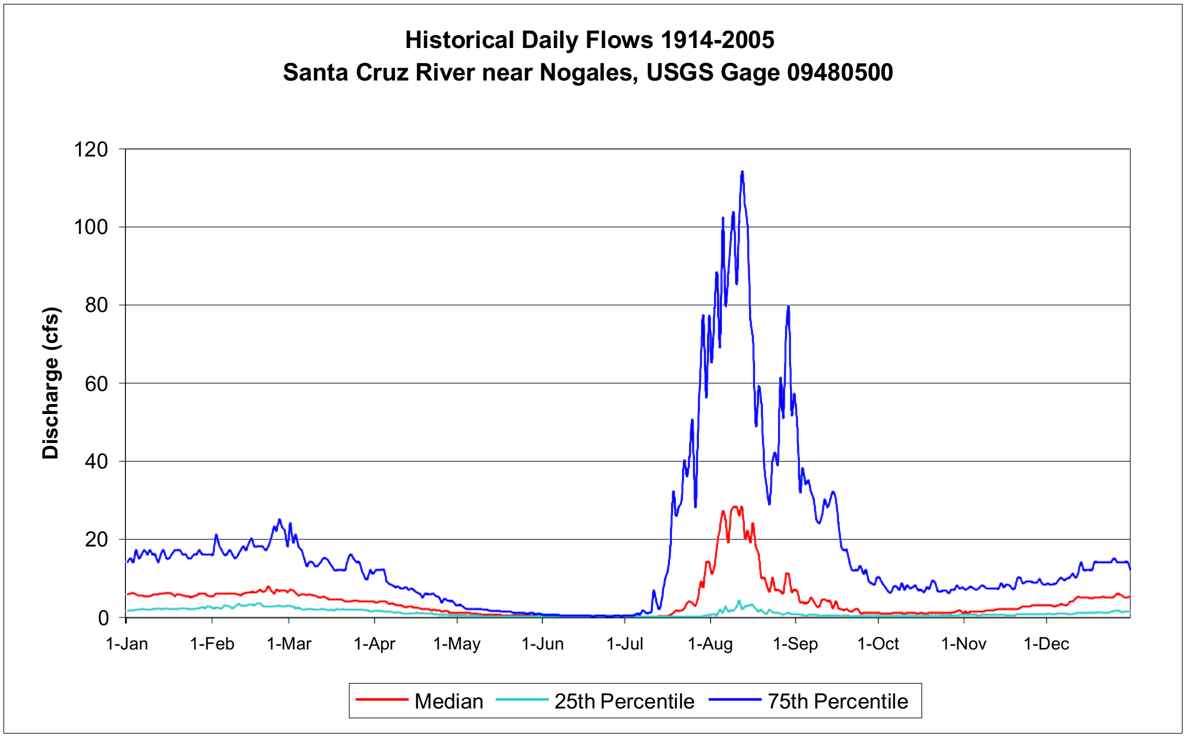

Figure 5-B. **Historical Daily Discharge at U.S.Geological Survey Gage 09480500, Santa Cruz River near Nogales.**

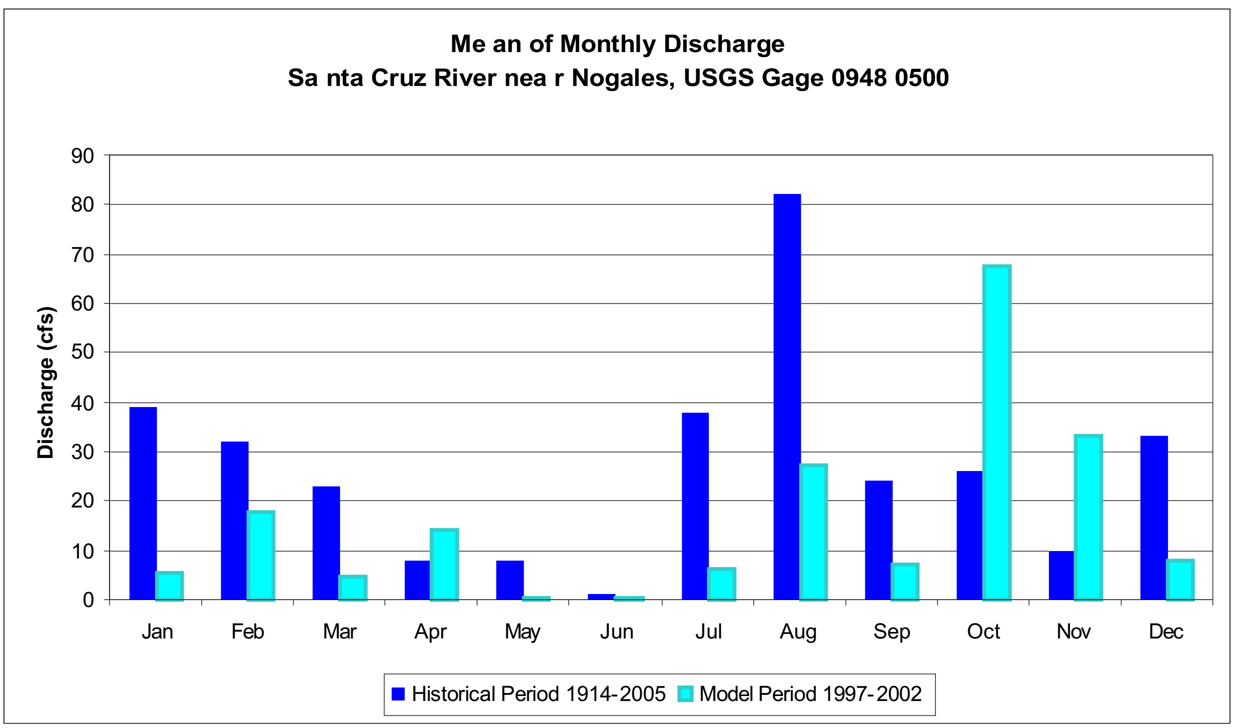

Figure 5-C. **Mean Monthly Daily Discharge at U.S. Geological Survey Gage 09480500, Santa Cruz River near Nogales.**

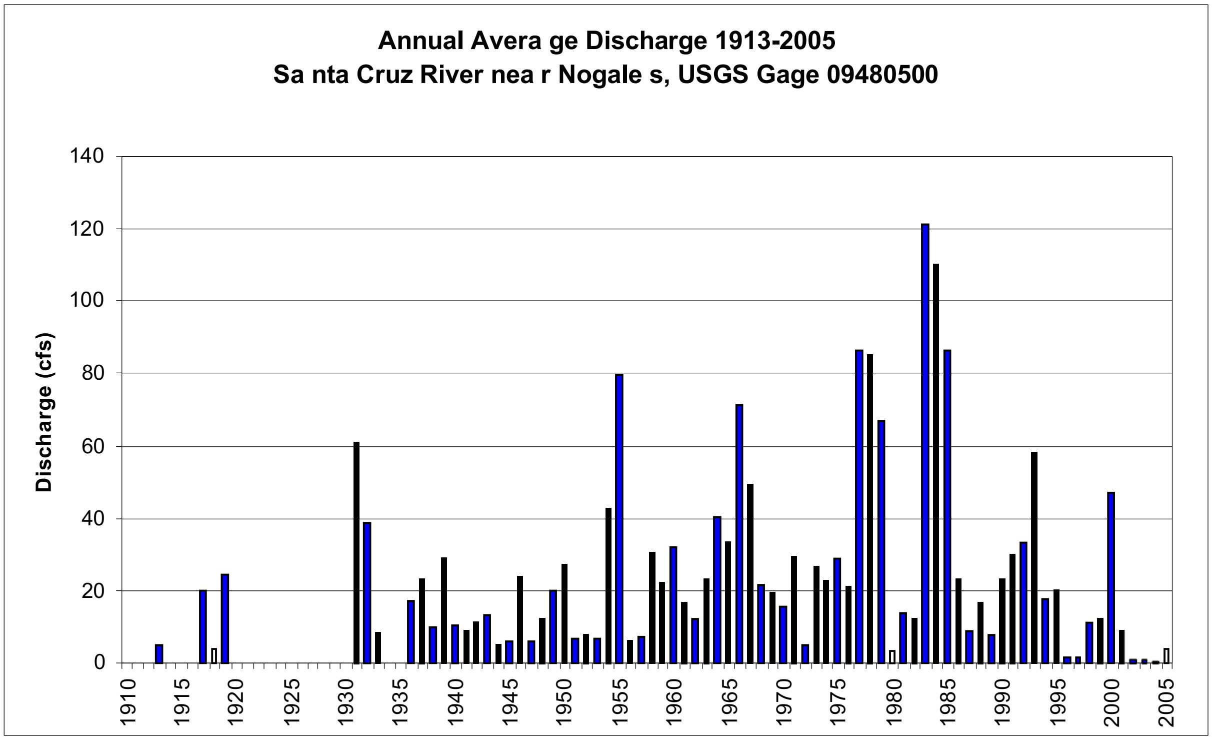

Figure 5-D. **Annual Mean Discharge 1913-2004 at U.S. Geological Gage 09480500, Santa Cruz River near Nogales.**

Duration Table of Daily Mean Flow for Period of Record 1914, 1917-19, 1931-33, 1936-89																
Discharge (cfs) which was equaled or exceeded for indicated percent of time																
1%	5%	10%	15%	20%	30%	40%	50%	60%	70%	80%	90%	95%	98%	99%	99.5%	99.9%
454	103	43	26	17	8.0	5.0	3.0	1.6	0.81	.33	0.0	0.0	0.0	0.0	0.0	0.0

Table 5-a. **Duration Table of Daily Mean Flow for Period of Record at U.S.Geological Survey Gage 09480500, Santa Cruz River near Nogales.**

Data Source: U.S. Geological Survey Statistical Summary, 1989.

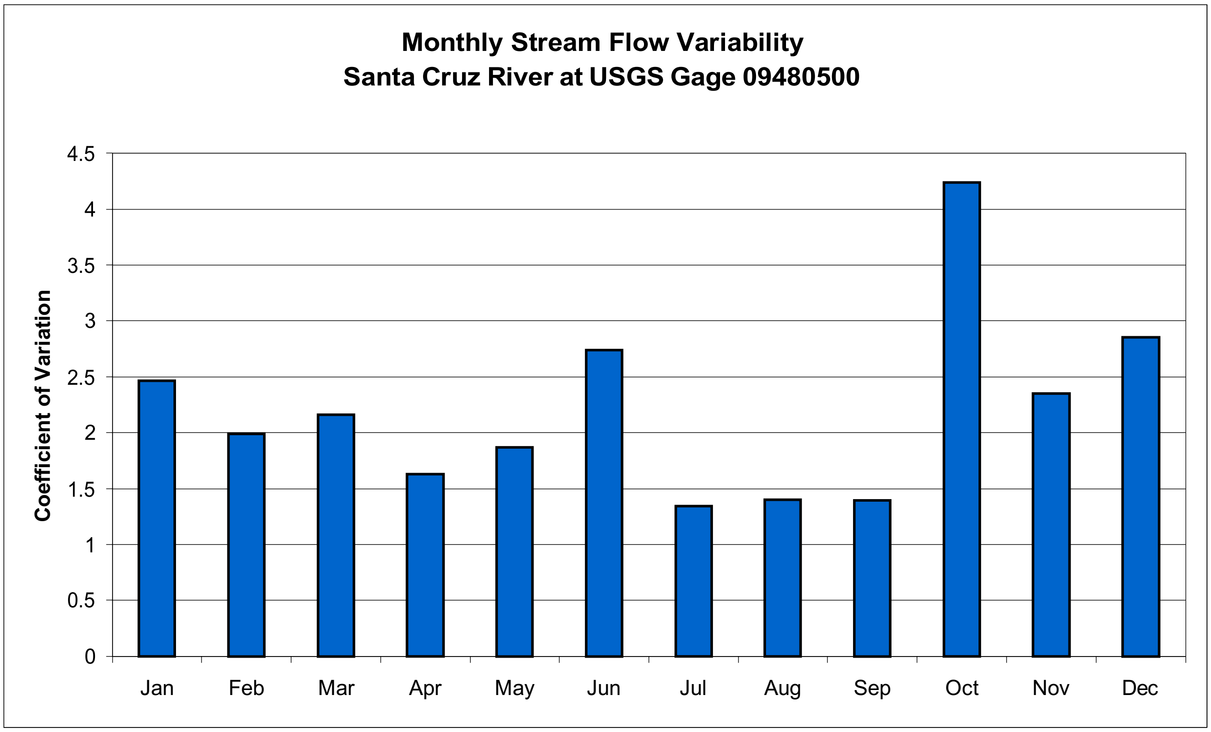

Figure 5-E. **Coefficient of Variation of Monthly Average Streamflows at U.S. Geological Gage 09480500, Santa Cruz River near Nogales.**

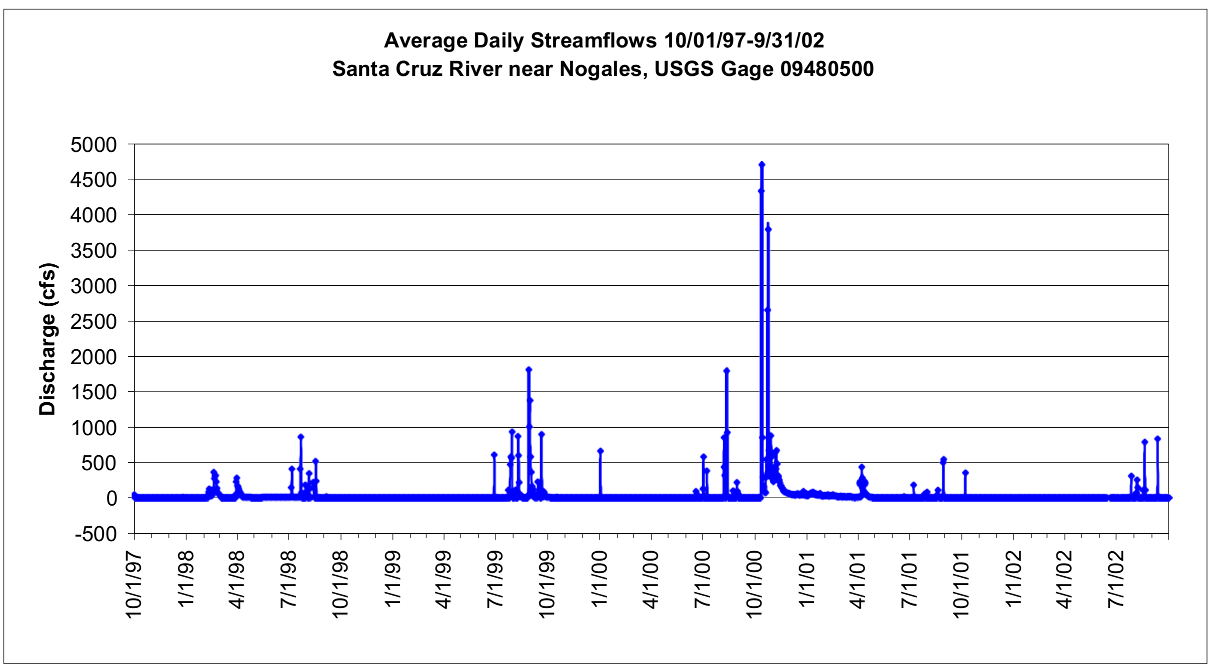

Figure 5-F. **Average Daily Streamflows for Study Period at U.S. Geological Survey Gage 09480500, Santa Cruz River near Nogales.**

Baseflow

Halpenny (1963) notes that prior to 1963 the Santa Cruz River was perennial through most of the area, and usually had a baseflow of one to two cubic feet per second. After about 1963 the riverbed had become dry most of the time because of the development of groundwater supplies in the inner valley. Groundwater pumpage in Mexico and the upstream microbasins allowed for more storage in the upstream aquifers resulting in baseflow infiltrating into the streambed. Putman (1983) notes that baseflow was minimal or non-existent at the U.S. Geological Survey Gage 09480500 at the time of his study. In recent times, baseflow is minimal at the gage and throughout the model area with the exception of Guevavi Narrows. Historically, even after baseflow disappeared in most of the river, baseflow continued to exist at the Guevavi Narrows. During the model period (water years 1998 through 2002), baseflow was seldom evident due to low precipitation.

Stresses such as groundwater pumpage in the Mexican reach of the Santa Cruz River have a significant effect on surface water flow into the United States. Surface water flow between San Lazaro and the International Boundary is mostly intermittent, however, surface water flow has been consistently observed during field activities at El Parque due to a bedrock constriction in the riverbed (Nelson and Erwin, 2001). An infiltration gallery in the stream channel and municipal wellfields are located adjacent to the river. Historically, streamflow in Mexico has been gaged irregularly. A stream gage referred to as the El Cajon gage was located 4.3 miles south of the town of Santa Cruz, Sonora and 3 miles upstream of the town of San Lazaro, Sonora. It was operated by the Mexican Section of the International Boundary and Water Commission from January 1954 to July 1974 when the gage was damaged by flooding and not repaired. The estimated mean annual discharge of the Santa Cruz River at the El Cajon gage for the period 1940–1946 and 1952-1968 was 7,000 acre-feet (Harshbarger, 1979). The gage is about six miles upstream from the infiltration galleries located in the riverbed, which comprise a significant source of domestic water supply for Nogales, Sonora. Some surface water flow measurements along the Santa Cruz River in Mexico are available between February 2000 and June 2001.

The magnitude and existence of baseflow is directly related to the available storage capacity within each microbasin. For example, during the 1998 El Nino event (mid-February to early April), intense precipitation and subsequent high-level runoff occurred. High infiltration rates of surface flow were observed and recorded along stretches where groundwater levels were relatively deep and storage space was available for recharge. Conversely, low infiltration rates have been observed when the groundwater microbasin(s) are at or near full capacity. Figure 5-G illustrates how quickly the aquifer responds to flow in the river. The microbasins act as underground storage reservoirs and can sustain groundwater discharge as baseflow along constricted down gradient areas such as Guevavi Narrows for many months following a flood event. It has also been observed that when water levels are within 20 feet of land surface at an observation well site in the Highway 82 microbasin, 55-619646, D-23-14 27add, groundwater discharge is observed as surface water flow down gradient at Guevavi Narrows (Nelson and Erwin, 2001). In the absence of runoff in the river, groundwater pumpage and evapotranspiration will reduce and eventually eliminate baseflow along intermittent reaches.

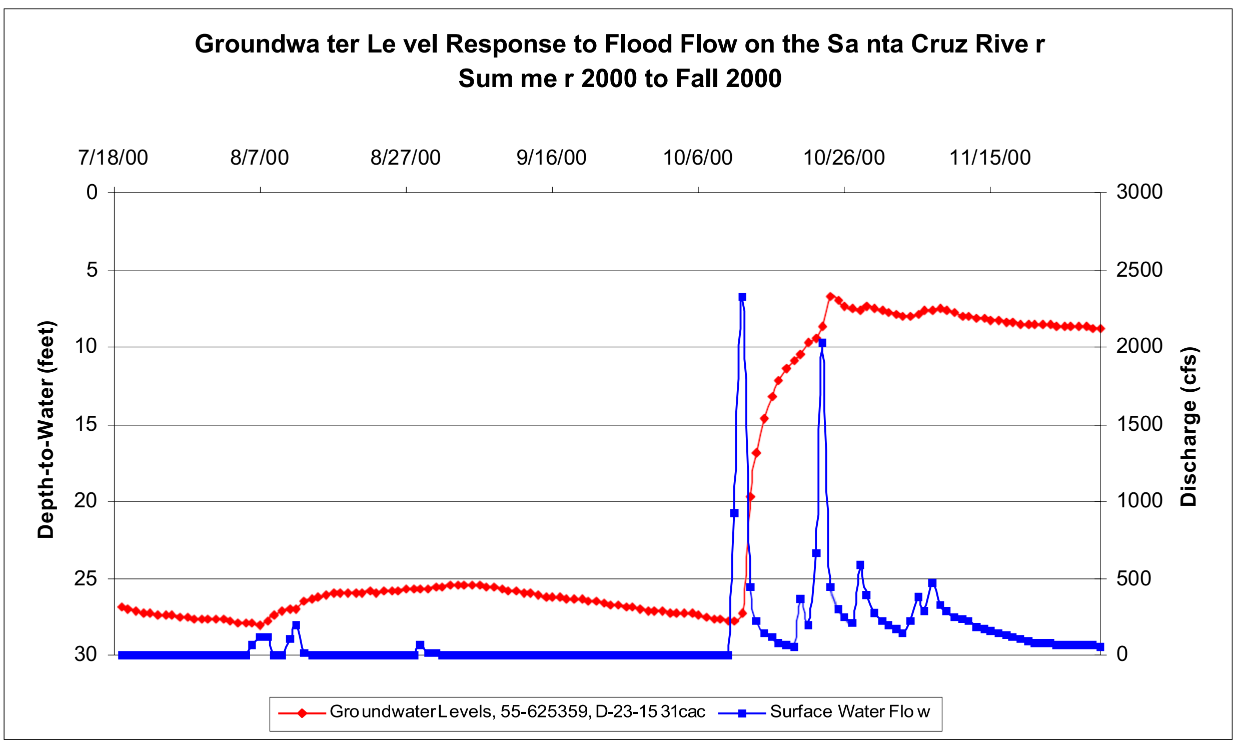

Figure 5-G. Groundwater Level Response at Kino Springs Well 55-625359 to Santa Cruz River Flow measured at U.S. Geological Survey Gage 9480500.

Groundwater Surface Water Interaction

The relationship between surface water flow and groundwater recharge due to flood events can be complex. For example, infrequent short duration flow events exceeding 1,000 cfs may induce little groundwater recharge and may have minimal associated recessional baseflow. However, records show that frequent flooding events such as those seen during the 1999 monsoons, or extremely large flood events have significant groundwater recharge and may sustain recessional baseflow for months.

Annual Discharge Volume

Table 5-b shows the total annual discharge calculated from the U.S. Geological Survey Gage 9480500 daily mean discharge values. Annual totals are based on water year October through September. The totals were derived by multiplying the average daily discharge (cfs) for each day of the year by time to obtain cubic feet per day and then totaling each year (365 days) separately. The historical median discharge at this location is approximately 13,500 acre-feet per year (1913-2002).

	1998	1999	2000	2001	2002
acre-feet/year	8,030	8,440	2,264	38,577	823

Table 5-b. Total Discharge for Water Years 1998-2002 at U.S. Geological Survey Gage 09480500 (acre-feet per year).

Tributaries

There are three tributaries in the model area that significantly contribute to the Santa Cruz River: 1) Brickwood Canyon, 2) Providencia Canyon, and 3) Guevavi Canyon. See Figure 5-A. Cumero Canyon and Burro Canyon were not included as stream segments, however their drainage areas were included within the broader drainage boundaries.

Tributary inflow rates were estimated on a proportional basis with respect to the flow and drainage characteristics established for the U.S. Geological Survey gage 9480500, Santa Cruz

River near Nogales. Average annual inflow for the tributaries was determined by using the methodology outlined by Otto Mooseburner (1970).

A multiple regression equation was used to estimate flow based on basin watershed area and annual precipitation. Average annual precipitation was estimated from a PRISM (Precipitation-elevation Regressions on Independent Slopes Model) map (Oregon Climate Service, 1995). PRISM is regression technique that distributes point measurements of monthly and annual precipitation to a geographic grid and has been evaluated and endorsed by climatologists and national agencies. Values for annual inflow from tributaries presented by Aldridge and Brown (1971) are similar to the results obtained using the Moosburner method.

Tributary Inflow (acre-feet)			
	Brickwood	**Providencia**	**Guevavi**
Historical Estimated Average Annual Tributary Inflow	350	1530	1130
Estimated Tributary Inflow for Study Period Water Years 1998-2002			
1998	210	920	680
1999	220	980	720
2000	60	260	1960
2001	1000	4440	3270
2002	20	90	70

Table 5-c. Estimated Annual Tributary Inflow for Santa Cruz Microbasin Model Area (rounded to the nearest 10 acre-feet).

Model inputs for the tributaries were adjusted yearly based on flows in the Santa Cruz River measured at the gage 09480500. As stated earlier, median annual flow measured at the gage 09480500, is approximately 13,500 acre-feet per year. (Median flow was used in this calculation as opposed to mean so that extreme flows would not heavily influence or misrepresent what "normally" occurs in the watershed.) Annual inflows at the gage for water years 1998–2002 were compared with the long-term median and calculated as a percentage of that median. That percentage was applied to the average annual tributary estimates for each year. Stress period inflow was calculated similarly. To obtain stress period flow for the tributaries, stress period.

flow at the Nogales gage was calculated as a percentage of the total annual flow. That percentage was applied to the average annual tributary flow calculated at that particular tributary Table 5-d is a conceptual water budget for the study period.

Conceptual Water Budget Water Years 1998 – 2002 (acre-feet)					
	WY 1998	**WY 1999**	**WY 2000**	**WY 2001**	**WY 2002**
Groundwater In					
Recharge					
Main Channel	4,130-6,290	4,350-6,630	1,180-1,790	5,720-8,580[1]	420-640
Mountain Front	1,370	1,370	1,370	1,370	1,370
Underflow					
Main Channel	400-600[1]	400-600[1]	400-600[1]	400-600[1]	400-600[1]
Total Groundwater In	**5,900-8,260**	**6,120-8,600**	**2,950-3,760**	**7,490-10,550**	**2,190-2,610**
Groundwater Out					
Riparian	3,600	3,600	3,600	3,600	3,600
Pumpage					
Municipal	2,840	2,440	2,680	2,460	2,940
Agricultural	360	360	300	220	150
Other	110	120	110	120	140
Total Pumpage	3,310	2,920	3,090	2,800	3,210
Underflow					
Main Channel	600-1,000[1]	600-1,000[1]	600-1,000[1]	600-1,000[1]	600-1,000[1]
Total Groundwater Out	**6,610-7,010**	**6,220-6,620**	**6,390-6,790**	**6,100-6,500**	**6,510-6,910**
Surface Water In					
Main Channel	8,030	8,440	2,290	38,580	820
Tributary	1,800	1,920	510	8,710	180
Total Surface Water In	**9,830**	**10,360**	**2,800**	**47,290**	**1,000**
Surface Water Out	**3,540-5,700**	**3,730-6,010**	**1,010-1,620**	**38,710-41,570**	**360-580**

Table 5-d. Conceptual Water Budget for Study Period – Water Years 1998-2002.

Chapter 6 - The Numerical Model

General Approach

The regional numerical model of the Santa Cruz AMA microbasins encompasses approximately 40 square miles. The model simulates transient surface water and groundwater flow conditions from October 1997 through September 2002. The model is three-dimensional, contains three layers, and simulates the interaction between the Santa Cruz River and the alluvial aquifer. The model accounts for underflow in and out of the area, groundwater recharge, evapotranspiration from phreatophyte growth, groundwater pumpage, surface water infiltration from streamflow and groundwater discharge to the streambed.

Selection of the Model Code

The model code selected for this study, Modular Three-Dimensional Finite-Difference Groundwater Flow Model 2000 (MODFLOW) developed by the U.S. Geological Survey (Harbaugh, et al, 2000; McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) was chosen to simulate the groundwater flow and groundwater surface water interaction in the microbasins. MODFLOW can simulate aquifer conditions that are confined, unconfined, confined and unconfined, and leaky. MODFLOW is designed to simulate aquifer systems in which (1) saturated-flow conditions exists, (2) Darcy's Law applies, (3) the density of groundwater is constant, and (4) the principal directions of horizontal hydraulic conductivity or transmissivity do not vary within the system (U.S. Geological Survey, 1997). MODFLOW simulates groundwater flow in aquifer systems using the finite difference method. It is the most widely used program in the world for simulating groundwater flow. The program has also been accepted in many court cases in the United States as a legitimate approach to analysis of groundwater systems (U.S. Geological Survey, 1997). Visual MODFLOW 4.1.126 (Waterloo Inc., 2004) was used as the pre-processor and post-processor, which simplifies the data input and analysis of the output. Refer to McDonald and Harbaugh (1988), Harbaugh and McDonald (1996) and Harbaugh, et al (2000) for a complete description of the model code.

Modeling Assumptions and Limitations

Several assumptions were made in order to reproduce the behavior of the hydrologic system in the microbasin model. Assumptions are necessary to simplify the very complex microbasin system so that it can be analyzed more easily. The goal is to simplify the conceptual model as much as possible yet retain enough complexity to satisfactorily replicate the system behavior (Andersen and Woessner, 1992). The assumptions also place certain limitations on the model as discussed below.

1) The Santa Cruz AMA microbasin groundwater flow model is a regional model. It is not intended to provide site-specific determinations of hydrologic conditions.
2) Hydraulic heads computed within each model cell represent the average within the saturated area of that cell.
3) Simulated groundwater recharge is applied directly and instantaneously to the uppermost active model cell as is dictated by the MODFLOW model code.
4) Recharge from precipitation falling directly on the groundwater basin area of the model domain is considered negligible except where it accumulates in tributaries and contributes to the main stem of the Santa Cruz River. Depth-to-water considerations in the older alluvium and Nogales Formation preclude effective recharge by direct precipitation in the areas away from the river. Shallower depth-to-water in the younger alluvium may be more conducive to effective recharge by direct precipitation. However, Halpenny (1963) notes that soil moisture tests before and after storms indicate recharge to the aquifer as negligible due to high evaporation rates and phreatophyte use.
5) The available water level data accurately represents the groundwater flow system within the model area. In the younger alluvium this assumption is reasonable. Outside of the younger alluvium data deficiencies are severe and the assumption is questionable.
6) The younger alluvium, older alluvium and Nogales Formation are treated as isotropic porous medium. Groundwater flow in all layers is considered laminar or non-turbulent and can be approximated using Darcy's equation. On a regional scale these assumptions are reasonable, however they may not apply on the local level due to non-laminar and

turbulent flow conditions that may exist in fractures or faults. This is particularly true in the older alluvium and Nogales Formation.

7) Evapotranspiration of the water table is considered negligible in the older alluvium and Nogales Formation as depths-to-water are generally greater than 50 feet.
8) The exchange of water between the streambed and aquifer is immediate as simulated by the Stream-Routing package. This is a reasonable assumption based on high infiltration rates in the younger alluvium and in consideration of relatively short stress periods and number of time steps.
9) The length of stress periods and number of time step lengths are appropriate to reasonably simulate the periodic recharge from short duration flow events on the mainstem of the Santa Cruz River.
10) MODFLOW assumes saturated flow conditions exist. Due to the small and shallow storage area in the younger alluvium this assumption does not always hold true in reality. Unsaturated conditions likely exist seasonally. Model instability and convergence problems occurred during calibration partially as a result of this condition.

General Characteristics of the Groundwater Model

Model Grid

The modeled area is divided into an orthogonal grid consisting of 88 rows and 82 columns. Cells are 1/8 mile by 1/8 mile (or 660 feet by 660 feet) for a total of 7,216 cells. The principle axis is aligned north/south and is closely aligned with the local baseline and meridian. It also generally parallels the Santa Cruz River. The active model domain corresponds to the valley between the Patagonia Mountains on the east and Mount Benedict on the west. See Figures 6-A and 6-B. Note that very little of the active model area occurs west of the Santa Cruz River. The younger alluvium is bounded on the west by hardrock and Nogales Formation.

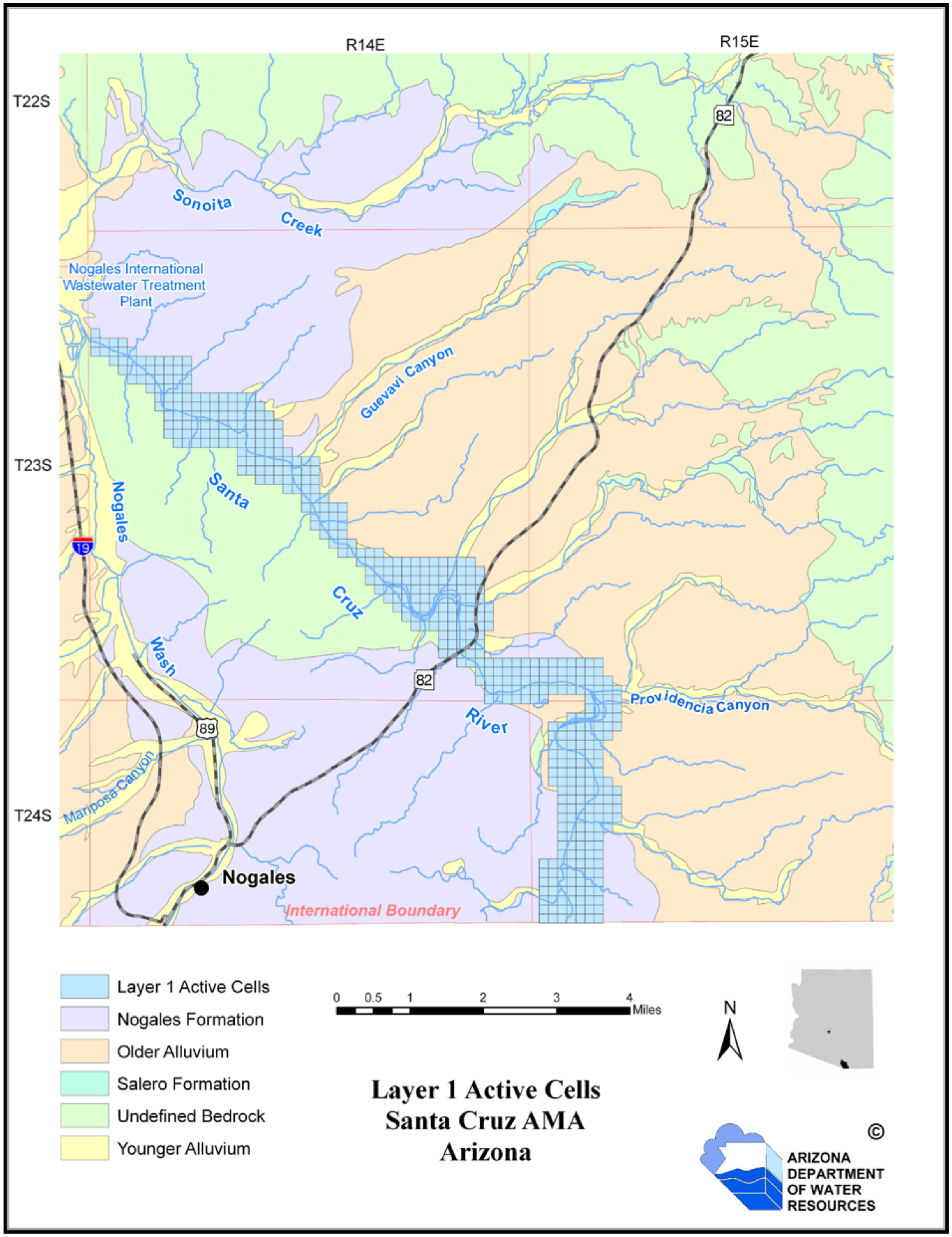

Figure 6-A. Map showing Location of Layer 1 Active Cells.

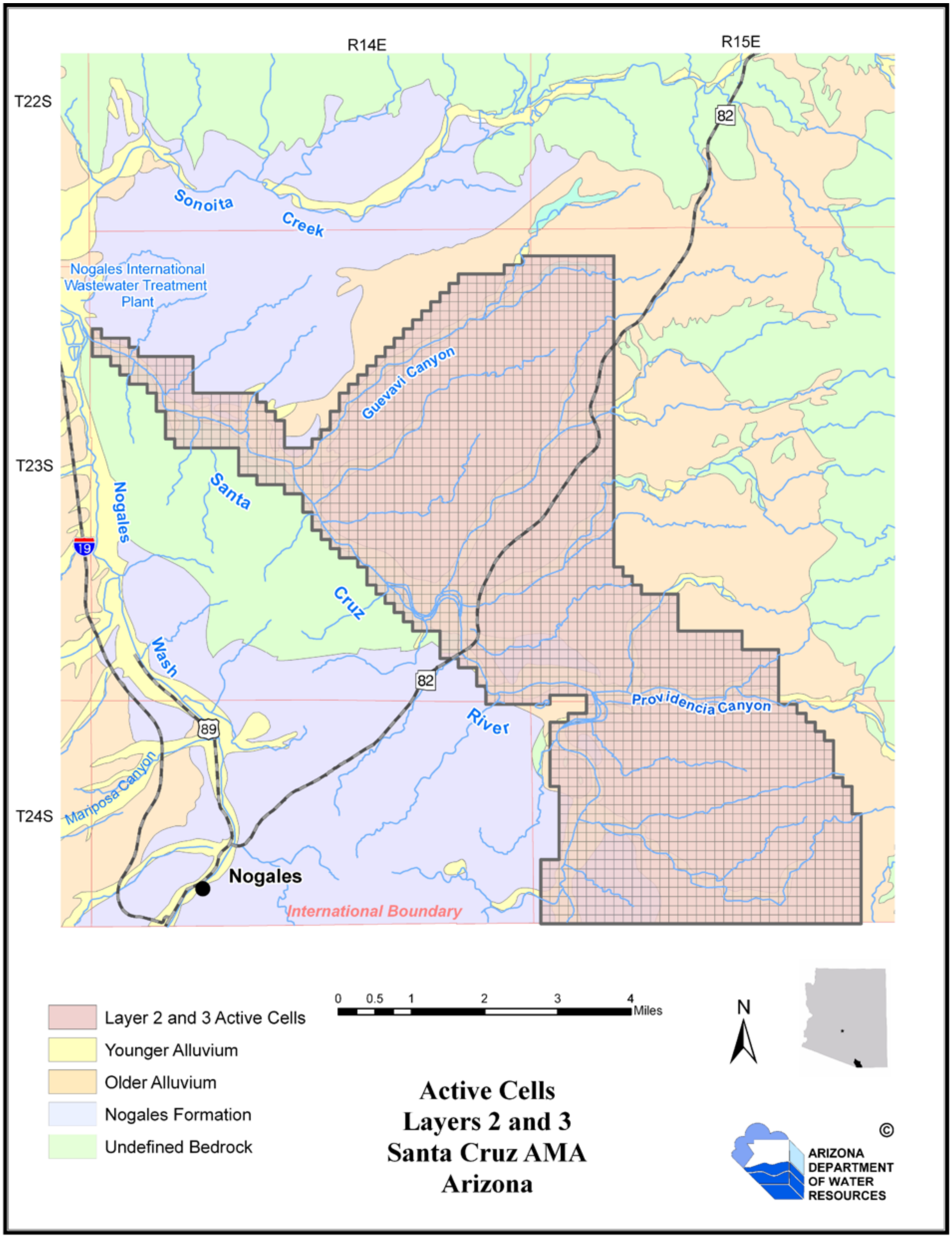

Figure 6-B. Map showing Location of Layer 2 and Layer 3 ActiveCells.

Input Packages

MODFLOW uses a modular structure wherein similar aquifer functions are grouped together into "modules" that are developed independently of each other. A variety of processes and features such as rivers, streams, drains, springs, reservoirs, wells, evapotranspiration, and recharge from precipitation and irrigation can be simulated (U.S. Geological Survey, 1997). This makes the model easy to customize.

The Santa Cruz AMA microbasin model was constructed using the following ten modules: 1) the BASIC package (BAS), 2) the Layer-Properties Flow package (LPF), 3) the Global Process Discretization file (DIS), 4) the Evapotranspiration package (EVT), 5) the Stream-Flow Routing package (STR), 6) the Horizontal Flow Boundary package (HFB), 7) the Well package (WEL), 8) the Recharge package (RCH), 9) the Constant Head Boundary package (CHD), and the 10) the General Head Boundary package (GHB). The Strongly Implicit Procedure (SIP) package was used for solving the flow equation.

The BASIC package contains information on the distribution of active and inactive cells, identification of constant head cells, and initial water levels.

The DIS package contains the length of model simulations and the physical structure of the aquifer system, including the top and bottom elevation of model cells and cell dimensions are included in the DIS package.

Aquifer parameters, such as hydraulic conductivity, transmissivity, vertical conductance (vcont) and storativity are included in the LPF package. The LPF package also contains the option of allowing cells to become dry and rewet. In an unconfined aquifer where a cell goes dry (the water table falls below the bottom of the cell) the cell converts to a no flow cell. This package allows the cell to rewet when the water table rises. The microbasins are very shallow and in reality, it is not uncommon for wells to go dry as in the recent past summer months. Conceptually, this allows the model to reproduce what actually happens in the field. However, when significant changes in storage, such as the rewetting of a previously dry cell, occur over a short period of time it can lead to convergence and stability problems during rewetting. Convergence occurs when the absolute value of head change within entire model domain reaches a preset limit. The microbasin model did experience convergence and stability problems.

Evapotranspiration

The Evapotranspiration package simulates groundwater discharge from the saturated zone based on the estimated riparian demand located primarily (but not limited to) the area near the river. Each model cell was assigned an evapotranspiration rate based on the phreatophyte study done by Masek (1996). See Chapter 3 for more information on the study. See Figure 6-C for the location of the evapotranspiration cells.

An average extinction depth (below which no evapotranspiration is assumed to occur) of 70 feet was used for modeling purposes. While this depth is far greater than the actual extinction depth of cottonwood and willows (approximately 10 to 30 feet), the depth was appropriate for modeling purposes because cell areas usually encompassed a mix of riparian vegetation that often included mesquite as well as cottonwood and willow. Additionally, the extinction depth was set deeper in many cells due to averaged land surface elevations. Land surface cell elevations were averaged using DEM data. The land surface in riparian areas located away from the main river channel were often assigned an averaged land surface elevation that was higher than actual land surface elevations on the side of the cell nearest the Santa Cruz River. Mesquite generally grows on the upper riparian terraces (Graf, W.L. et al, 1984). This resulted in some cells with dense vegetation being too far above the water table hence necessitating the extension of the extinction depth. Additionally, it was necessary to expand layer one beyond the area of younger alluvium as defined by Simons (1974) in order to accommodate all of the riparian vegetation.

Pumpage

The Well package simulates groundwater pumpage from aquifer systems in the model area. Well pumpage was assigned monthly based on annual reporting and estimates of agricultural pumpage. As mentioned previously, the limited storage space in the younger alluvium is often quickly depleted due to intense local pumping of municipal wells. Therefore, the City of Nogales staggers individual well pumpage to allow the aquifer to recover. Initially the monthly volume pumped for each well as reported by the City was used as input. That volume was converted to an average rate for the month. However this approach changed, and some well pumpage was split between cells and varied over time to avoid dewatering model cells. Because

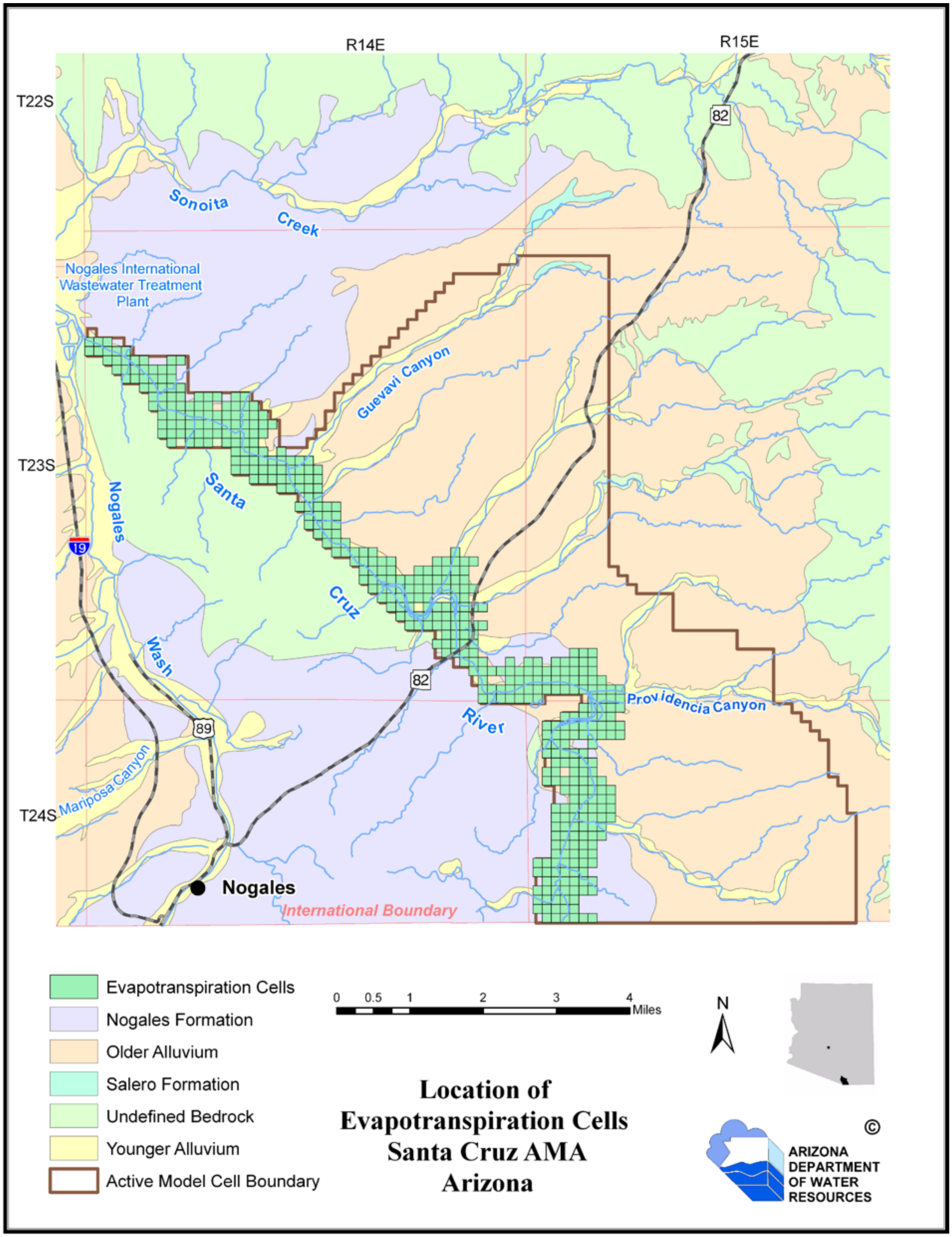

Figure 6-C. Map showing Location of Evapotranspiration Cells.

the aquifer space is so limited (both in reality and in the model) some wells were not simulated to be continuously pumped in conjunction with other continuously pumped wells
This approach was realistic and consistent with the City's practice of using a staggered pumpage schedule.

Pumpage was distributed areally throughout the model area based on estimates and well-specific pumpage records. Pumpage was vertically distributed throughout the model area based on available well data. For wells with construction information, the pumpage was distributed vertically to the model layers based upon reported perforated intervals and well depths. For wells without construction information, pumpage in the younger alluvium was distributed to the uppermost model layer that represents the younger alluvial aquifer. For wells in the older alluvium and Nogales Formation without construction information, estimates

The Horizontal Flow Boundary package simulates thin, vertical, and low-permeability geologic features. It adjusts hydraulic conductance between adjacent cells in a layer. The package was used in the microbasin model to simulate the bedrock, which protrudes above the surface of the streambed at Guevavi Narrows. Figure 6-D shows the location of horizontal flow boundary, constant head boundary and general head boundary cells.

The Recharge package was utilized to simulate mountain front recharge to the older alluvial aquifer. The recharge is applied to the uppermost active layer in the mountain front areas, which would be layer 2 in the microbasin model. Figure 6-E shows the location of the recharge cells.

The Stream-Flow Routing package simulates the interaction between surface streams and groundwater. It is not a true surface water flow model. It is more of an accounting program that tracks the flow in the stream as it interacts with the groundwater system (Prudic, 1989). The microbasin model had 10 stream segments including the 3 tributaries. Figure 6-F shows the location of the stream cells.

The Strongly Implicit Procedure package was used as the method for solving the large system of simultaneous linear finite-difference equations by iteration.

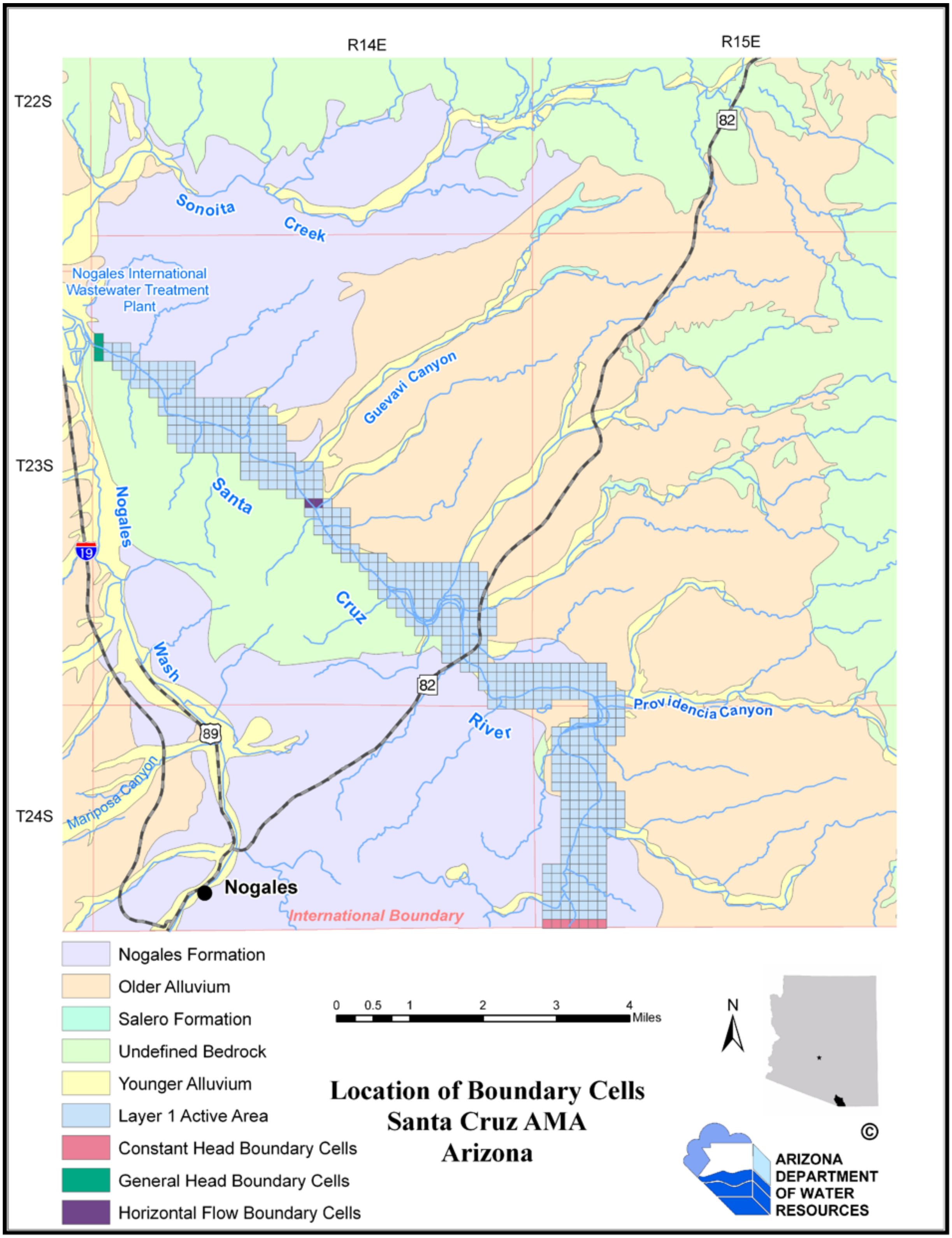

Figure 6-D. Map showing Location of Boundary Cells.

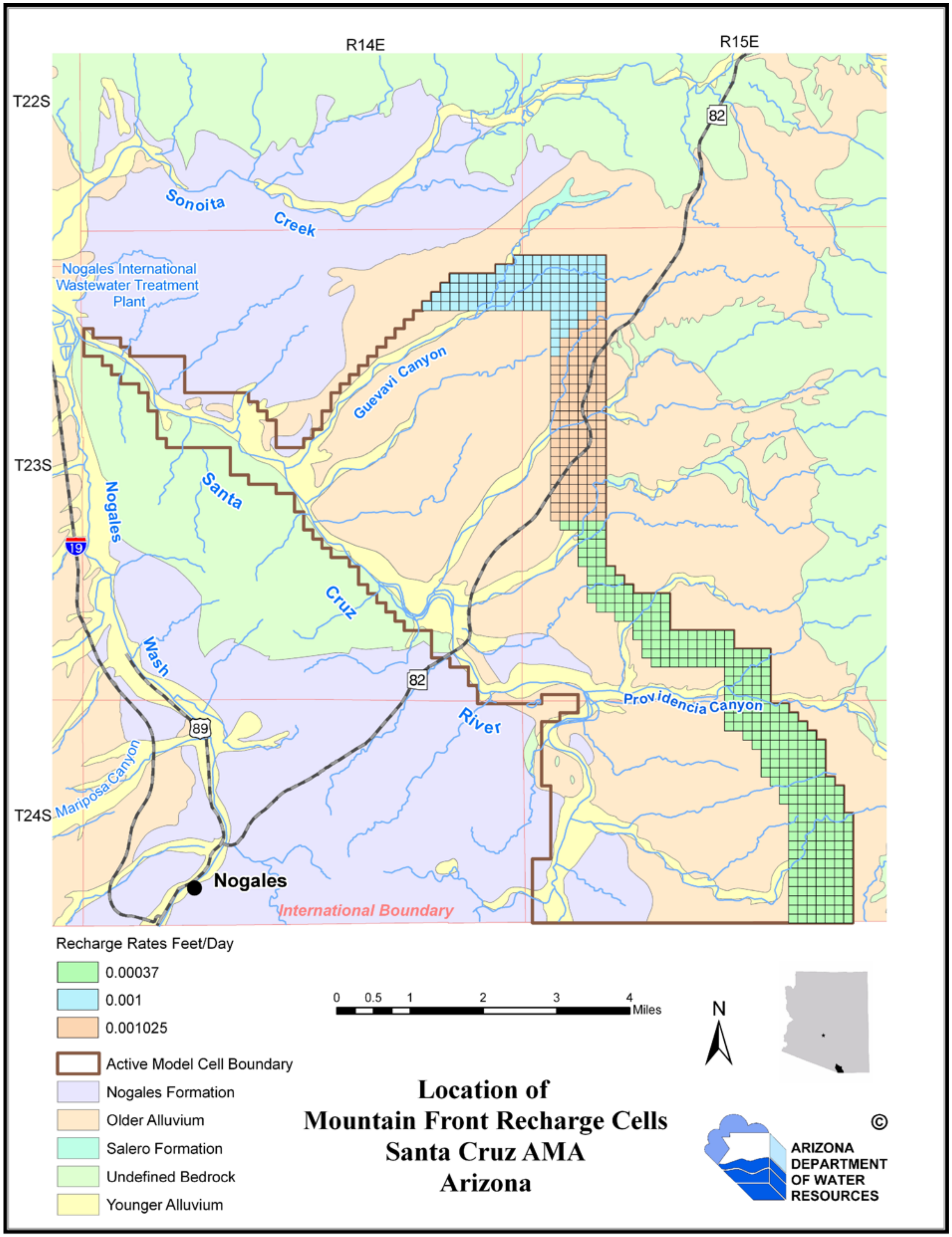

Figure 6-E. **Map showing Location of Mountain Front Recharge Cells.**

Model Layers and Aquifer Conditions

The model was constructed with three layers representing the three stratigraphic units in the area: 1) layer 1 – younger alluvium, 2) layer 2 – older alluvium, and 3) layer 3 – Nogales Formation. Layer 1 is defined as unconfined and layer 2 is defined as convertible or confined/unconfined. Layer 3 is defined as confined. Layer thickness was defined by geologic contact elevations when available. These elevations were derived from a number of sources including the well driller's log program (ADWR, 2003), geologic map by Simons (1974), and a geologic report by Gettings and Houser (1997). Very little information was available to determine the total thickness of Layer 3. Therefore, it was modeled solely by its transmissivity and a uniform thickness of 600 feet was assigned.

Boundary Conditions

The selection of proper model boundary cell types is essential to the accuracy of the model. Boundary cells define the hydrologic conditions along the model borders. Inactive model cells or no flow cells are those for which no groundwater flow into or out of the cell is permitted. No flow cells in the model correspond to either bedrock outcrops, for example, Mount Benedict or in some locations, Nogales Formation.

There are two types of active cells, variable head and constant head cells. Variable head model cells allow the water level elevation in the cell to fluctuate with time. These cells comprise the active simulated region within the model domain. Constant head cells are those for which the water level elevation in the cell is held constant at a specified elevation. Constant head cells keep the water level elevation constant along the model boundary. Constant head cells allow the groundwater flux into or out of the cell to change in response to changing hydraulic conditions. Constant head cells are used in the younger alluvium to simulate underflow into the model area from the south or Mexico.

General head boundary cells were used to simulate underflow out of the model area in the Eagan Narrows area. General head boundary cells require an external "reference head" to be assigned to each general head boundary cell. The reference head corresponds to groundwater conditions in an area outside the model domain where groundwater levels remain constant over specific time periods. For the SCAMA model the northern general head boundary cell reference elevation was based on water level measurements from a well in the Guevavi microbasin, 55-619649, and a well in the NIWTP model near Sonoita Creek, 55-506506. The latter well is upstream of the NIWTP and does not appear to respond to releases from the plant. Water levels were changed seasonally as field data was collected.

Vertical Leakance and Vertical Hydraulic Conductivity

Vertical leakance between layers is usually modeled by using the VCONT option in MODFLOW. VCONT is calculated outside the model and then input as an array. Visual MODFLOW calculates interlayer leakage or VCONT using information already in the model such as the cell top and bottom elevations, hydraulic conductivity (Kx, Ky, and Kz), and hydraulic head and does not store the information. According to Halpenny (1963) and Halpenny and Halpenny (1983), the horizontal to vertical hydraulic conductivity ratio was determined to be 10:1 in the younger alluvium and Salero Formation. Due to the lack of data and based on parameter estimation in the NIWTP model (Nelson, 2007) horizontal to vertical hydraulic conductivity was considered to be a 10:1 ratio in the older alluvium and Nogales Formation as well.

Stream –Aquifer Interaction

Ten stream segments totaling approximately 12 miles are assigned in the model. Seven segments are associated with the main channel of the Santa Cruz River. Three tributaries: Brickwood Canyon, Providencia Canyon, and Guevavi Canyon intersect the main channel. Flows recorded at the U.S. Geological Survey Gage 09480500 were averaged for each stress period and applied to stream segment 2. Input for each tributary was based on the flows at the gage as addressed in Chapter 5. The location of stream cells is shown in Figure 6-G. (Stress periods were based on periods of relatively consistent flows. Stress period dates and days are in Appendix A.)

Conductance of the streambed is a component of the Stream-Routing package developed by Prudic (1989) that permits the modeling of the hydraulic interconnection between the surface water feature and the groundwater system. The conductance value is a product of the streambed

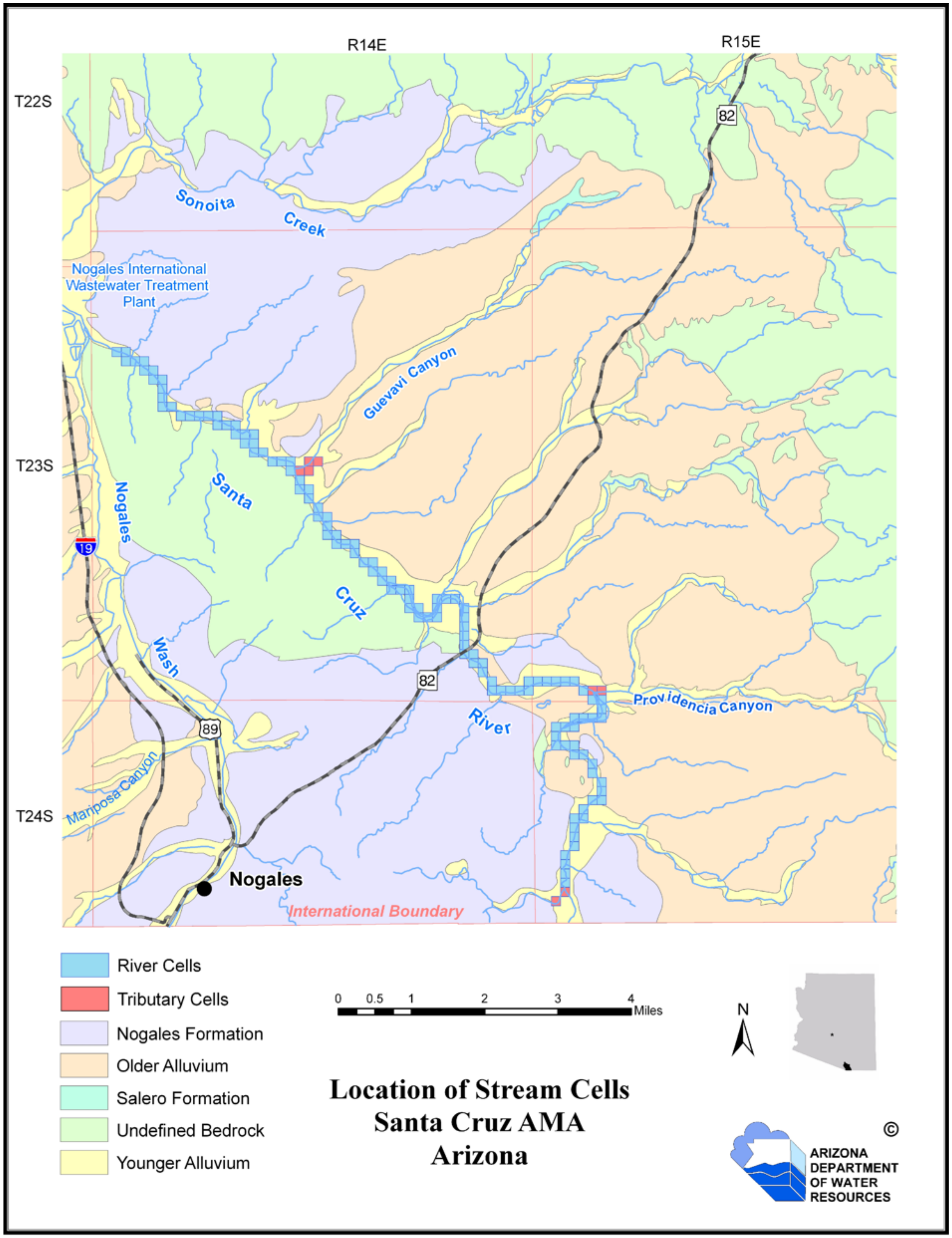

Figure 6-F. Map showing Location of Stream Cells.

vertical hydraulic conductivity, stream width, and stream length per model cell (i.e., wetted area) divided by the streambed thickness. The dimensions of the river were estimated based on rating curve data from U.S. Geological Survey gage 90480500, Santa Cruz River near Nogales and field observations. A linear relationship ($7.65Q^{.4722}$, $R^2 = .86$) was identified between stream width and discharge from the rating curve data. A linear relationship between stage and discharge could not be identified, so based on cross-section measurements taken during seepage runs and the ratings curve data an estimate was developed based on discharge. The dimensions were assumed to be constant throughout the entire length of the main channel. Stream stage and width were manually varied each time step based on the rate of flow applied in segment 2. Streambed top elevations were derived from a field survey by Tatlow (2003) and were entered for each segment. Streambed top elevations for reaches between the segments were calculated by linear interpolation in Visual MODFLOW (Waterloo, Inc., 2004). Stream length was calculated for each reach by Visual MODFLOW. A streambed thickness of 5 feet was used based on an optimal calibration in the NIWTP model (Nelson, 2007). The vertical hydraulic conductivity of 2 feet per day was used for all segments also based on an optimal calibration in the NIWTP model during periods where no clogging layer in the stream channel existed (Nelson, 2007). Data for the 94 time steps is available in Appendix B.

Aquifer Parameters

Hydraulic conductivity, transmissivity, specific yield and storativity were estimated for each hydrogeologic unit within the model area. Transmissivity and hydraulic conductivity were estimated for the younger alluvium (model layer 1) from aquifer tests performed by Halpenny, 1963 and ADWR, 1982. Transmissivity and hydraulic conductivity for the older alluvium and the Nogales Formation were estimated from aquifer tests performed by Earl H. Williams Well Drilling, 1977; Manera, 1980; Halpenny and Halpenny, 1985; and Halpenny, 1981 and 1983. Specific yield in the younger alluvium was estimated using a gravity survey conducted by Tatlow and Nelson (1999) and aquifer tests mentioned above. Storativity for the older alluvium and Nogales Formation were derived from aquifer tests. Due to the lack of data in some areas, storativity estimates of the older alluvium and Nogales Formation were obtained from the NIWTP model (Nelson, 2007). The initial averages of each parameter that were developed and used in the model are provided in Table 6-a. Values of hydraulic conductivity are shown in Figures 6-G, 6-H, and 6-I.

	Initial Average	
Horizontal Hydraulic Conductivity		
Layer 1 - Yal		
Buena Vista	350 Ft/Day	
Kino Springs	600 Ft/Day	
Highway 82	600 Ft/Day	
Guevavi	500 Ft/Day	
Layer 2		
Oal - Southern Area	0.3 Ft/Day	
Oal - Central Area	0.3 Ft/Day	
Salero Formation	5 - 35 Ft/Day	
Layer 3 – Nogales Fm.	.4 - .5 Ft/Day	
Specific Yield		
Layer 1 - Yal		
Buena Vista	.14 - .17	
Kino Springs	.14 - .20	
Highway 82	.14 - .20	
Guevavi	.14 - .20	
Layer 2 - Oal	.0014 - .0001	
Salero Formation	.1 - .15	
Layer 3 – Nogales Fm.	.00011	
Specific Storage		
	Storage Coefficient	Specific Storage (1/feet)
Layer 1 - Yal	N/A	N/A
Layer 2 - Oal	.0014 - .0001	3.5e-6
Salero Formation	.1 - .15	.0005
Layer 3 – Nogales Fm.	.00011	6.67e-6

Table 6-a. Initial Input for Hydraulic Parameters.

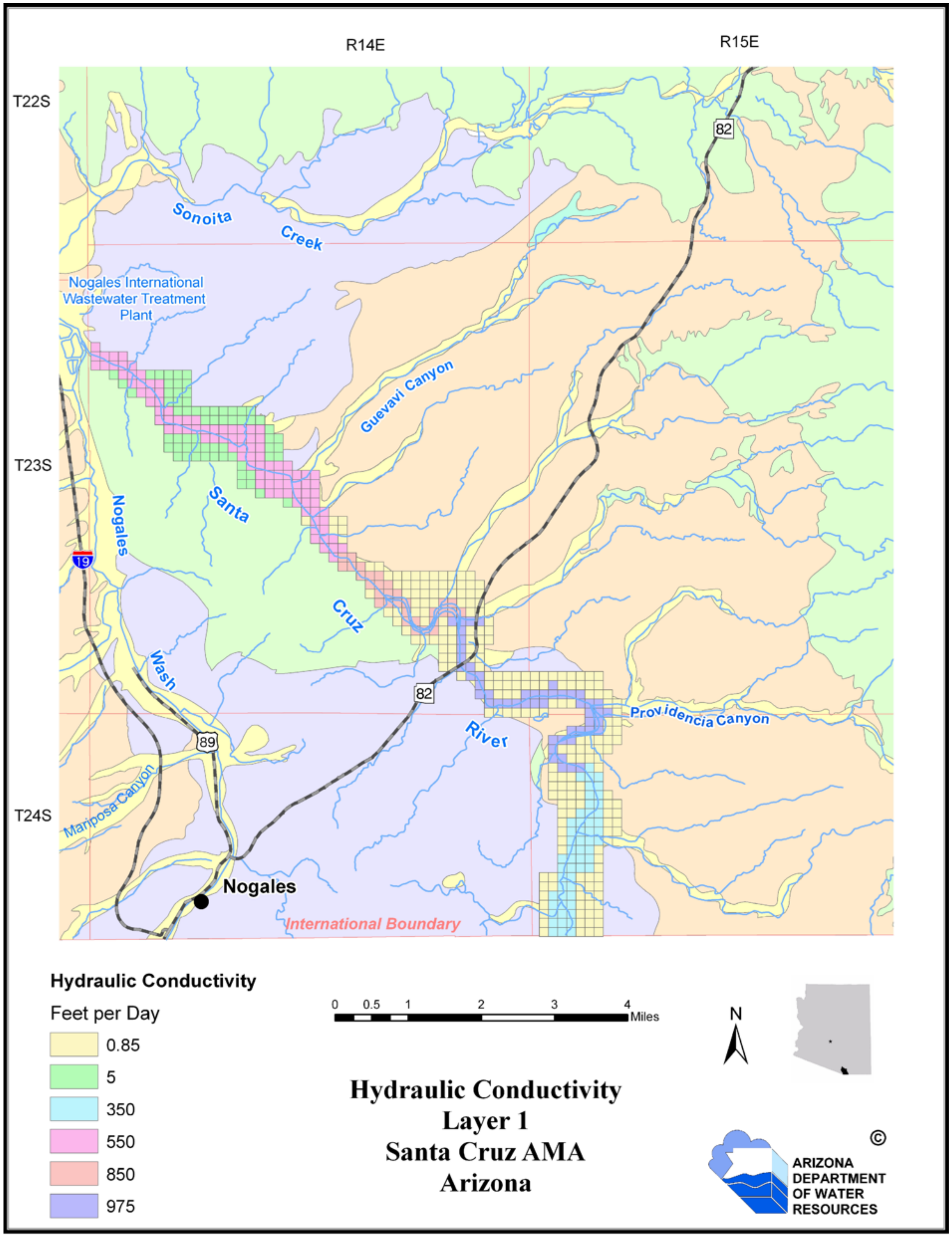

Figure 6-G. Map showing Hydraulic Conductivity in Layer 1.

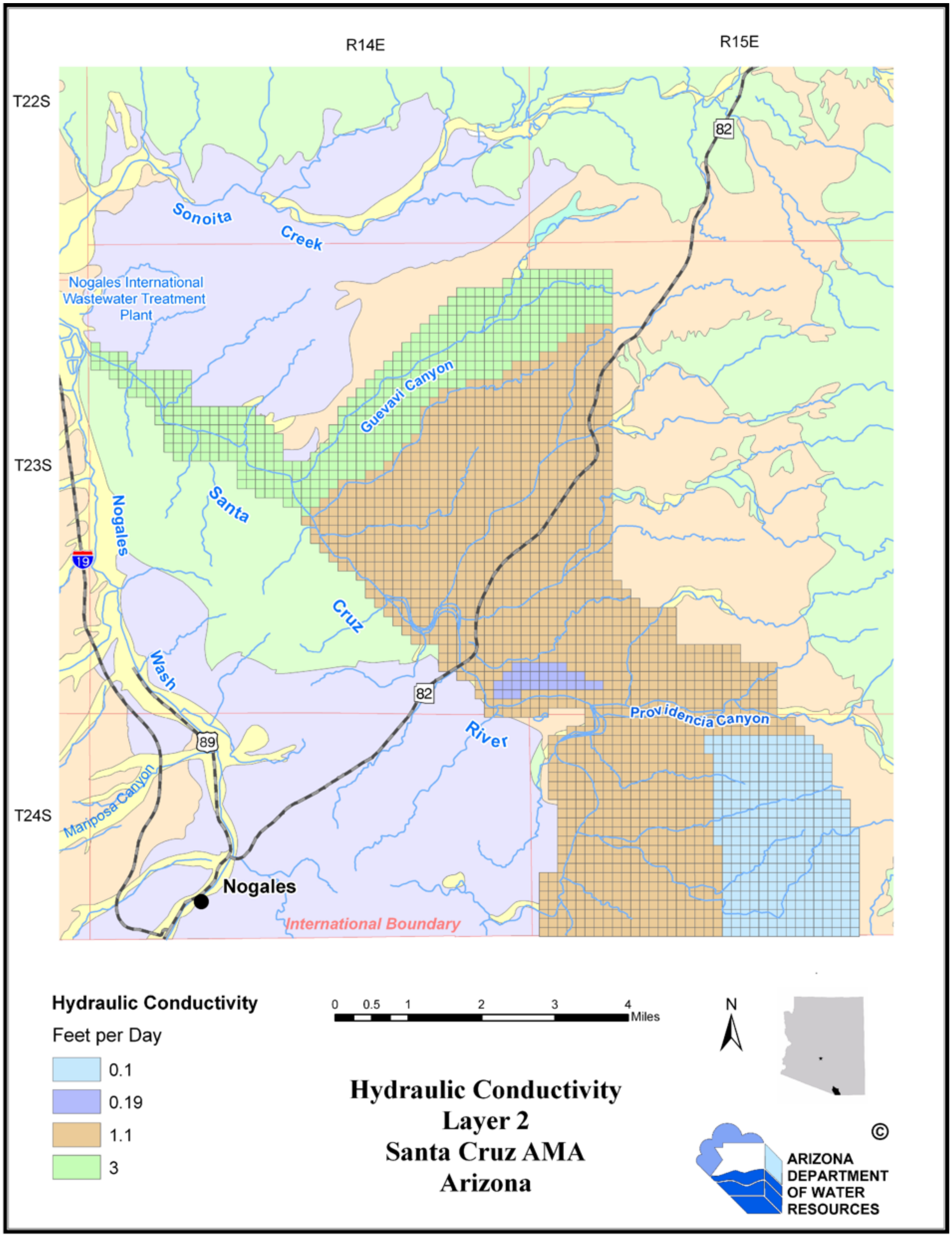

Figure 6-H. Map showing Hydraulic Conductivity in Layer 2.

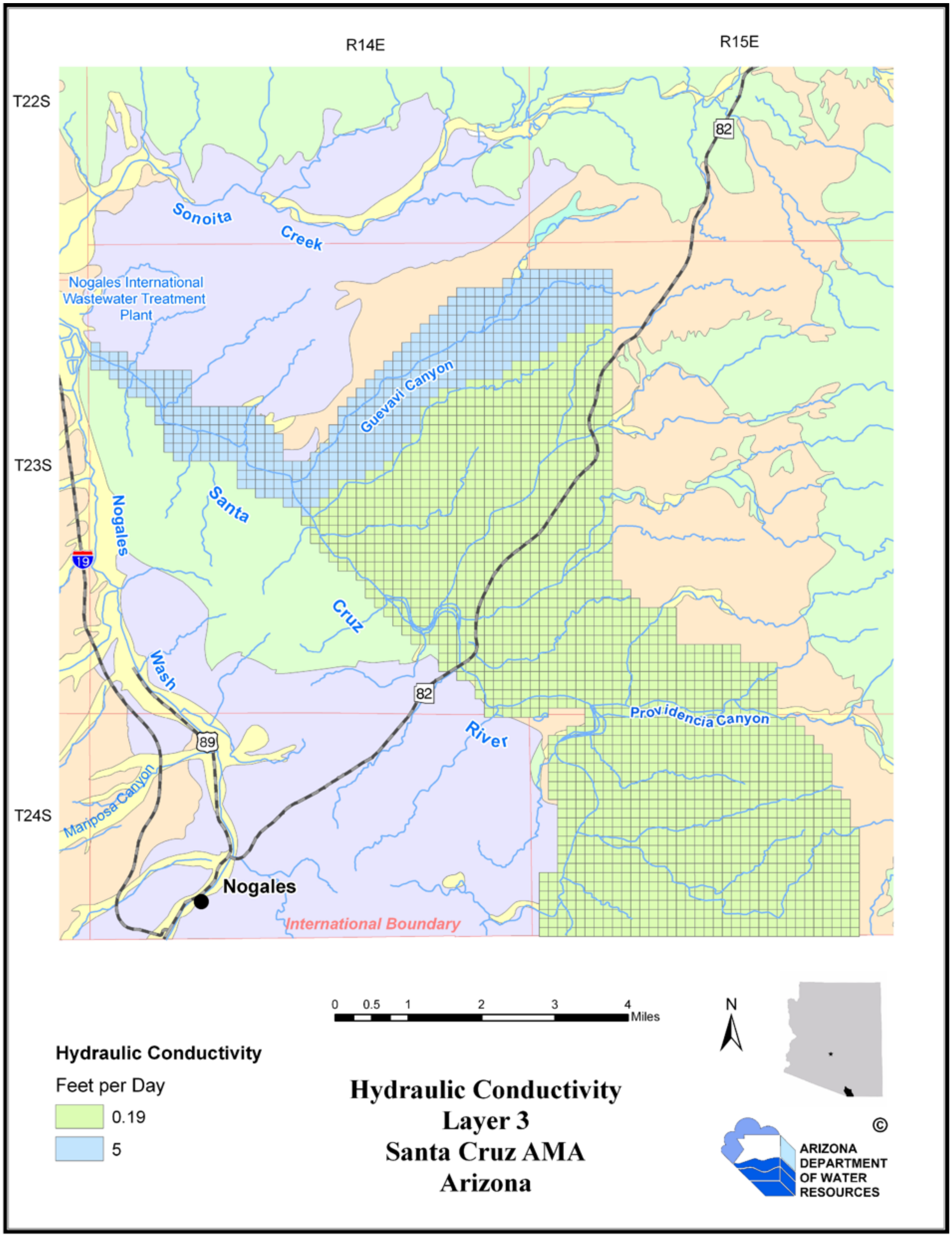

Figure 6-I. Map showing Hydraulic Conductivity in Layer 3.

Basic Data Requirements

Data Estimation and Discretization

The basic geologic and hydrologic data inputs to the groundwater flow model have been discussed earlier in this report. As mentioned previously, there were many data deficient areas where geologic and/or hydrologic data were unavailable, particularly in the older alluvium and Nogales Formation. Due to these deficiencies it was necessary to estimate model data inputs over much of the model domain.

In some instances model data were estimated and contoured using geographic information systems (GIS) based on analysis of the available data. The discrete data inputs that were required for each active model cell were generally obtained using a computerized discretization process.

Water Level Data

Younger alluvium

Water level data for the younger alluvium were provided by nine wells located along the river. Water levels were measured approximately monthly for the observation wells during the calibration period. Transducers measuring daily (or in some cases, more often) water levels were installed on three wells at varying time periods during the calibration period. See Figure 6-F for locations of all observation wells.

Older alluvium and Nogales Formation

There are very little water level data available for the older alluvium and Nogales Formation particularly during the calibration period. Data were available from approximately 5 wells for a 40 square mile area. Unfortunately, only 14 actual measurements were available during the calibration period and three of those were instances where the well was either being pumped or recently pumped.

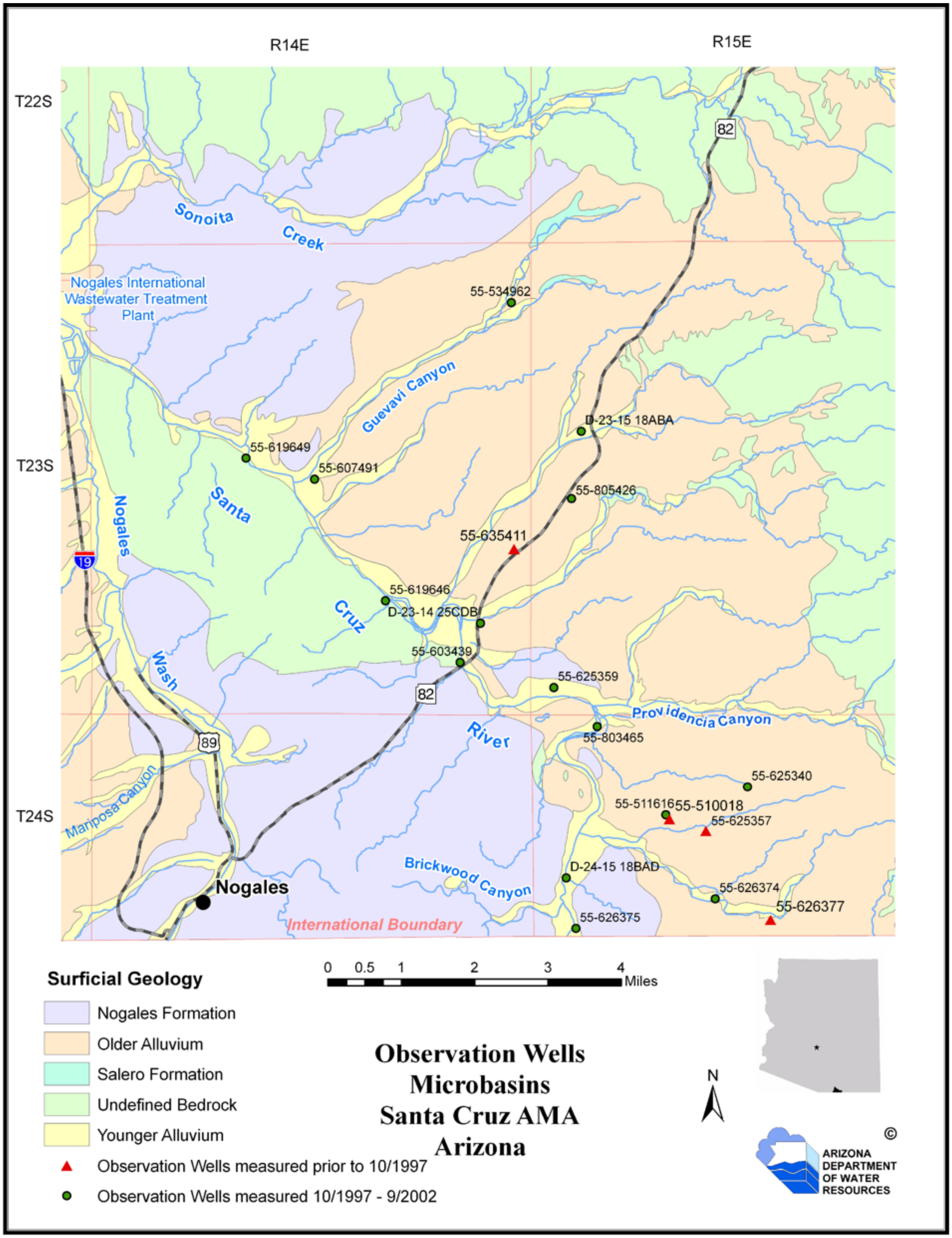

Figure 6-J. **Map showing Location of Observation Wells.**

Initial water levels were derived from an area-wide water level elevation map (Figures 4-A and 4-B) prepared by ADWR. Even though very little data exists in the older alluvium and Nogales Formation during the modeling period, the available historical data indicates little change in water levels over time. This statement must be further qualified to note that water level measurements are only available from 1980 to present (with the exception of two measurements) and are temporally irregular. With consideration of the available data, it was assumed that the water levels used during the calibration period were representative of layer 2 and layer 3 in general.

Groundwater Recharge Data

Groundwater recharge data were supplied by Osterkamp, 1973. Recharge inputs consisted of natural recharge along mountain fronts and ephemeral stream channel infiltration.

Groundwater Pumpage Data

Groundwater pumpage data were derived from the ADWR-ROGR database and from the City of Nogales.

Aquifer Parameter and Geologic Data

Aquifer parameter data (hydraulic conductivity, specific yield, storage coefficient) and geologic data (top and bottom elevations of model layers) were obtained from several aquifer tests, specific capacity measurements, and others (See Chapters 2 and 3). A tabulation of aquifer parameter and related data is provided in Table 6-a.

Model Characteristics	***Description***	***Model Units***
Transient state	October 1997 – September 2002	Time = Days
Model Grid	88 rows x 82 columns	Length = Feet
Model Cells	No Flow, Constant Head, General Head, Horizontal Flow and Variable Head	660 square feet or 10 acres
Model Layers	3 layers of variable thickness	Length = Feet
Layer 1 Layer 2 Layer 3	Unconfined aquifer Unconfined/confined Confined	
Recharge	Applied to uppermost active cell	Feet/Day
Stream-Routing	Hydraulic interconnection of Santa Cruz River with the younger alluvium – layer1	
Pumpage	Derived from all three layers	Feet^3/Day
Evapotranspiration	Extinction depth 70 feet from model layer 1 only	Feet/Day
Horizontal Hydraulic Conductivity	Estimates from aquifer tests.	Feet/Day
Vertical Hydraulic Conductivity	1:10 all layers	Feet/Day
Storage Term	Specific Yield Storage Coefficient Specific Storage	Dimensionless Dimensionless 1/Feet
Solution Techniques (Numerical Solver)	Strongly Implicit Procedure Closure Criteria = .01	 Feet
Time Discretization	Stress Periods = 94 Time Steps = 10 per stress period	

Table 6-b. Model Input Descriptions and Units.

Chapter 7 – Calibration

Selection of the Calibration Period

The Santa Cruz AMA groundwater model was initially structured to include the entire Santa Cruz River Valley from the El Cajon stream gage in Mexico (near the village of San Lazaro) to the Santa Cruz / Pima County line in the United States. The Potrero Canyon area was also included. Early in the model development attempts to calibrate the model based on pre-development conditions (1952) were unsuccessful. A substantial lack of data presented large obstacles for modeling in Mexico. In the United States, temporal data were not available. Annual stresses do not address the dynamic nature of the microbasins. Applying annual stresses resulted in a set of water levels that may have been representative of the year but not accurate enough to use as starting heads in a transient simulation. It is imperative that starting water levels for the simulation are always as accurate as possible, basically within just a few feet. Storage space is so limited that differences of plus or minus 10 feet can represent large percentages of changes in storage. This would result in an inaccurate calibration for any runs after the pre-development run.

Additionally, the distinct differences in the hydrologic regimes of the various areas were also noted. As a result, in 2001 the model was sub-divided into the NIWTP and microbasin models. The area in Mexico was dropped for lack of data and the Potrero area may be modeled at a later date. The resulting models were then calibrated to observed (three to four week intervals) seasonal water level and streamflow data between 1997 and 2002. In the microbasins, temporal calibration is an important component of the overall calibration for valid results. Concentrated temporal data were not available before the Department began the monitoring program in 1997.

Initial Conditions

It is standard practice to select a steady state head solution generated by a calibrated model as the initial conditions for a transient state model. Steady state conditions require that the groundwater system inflows equal the groundwater system outflows. Assumptions associated with equilibrated conditions also require that no water is added or removed from aquifer storage. These requisite conditions inherently pose problems for the microbasins due to their dynamic nature. The microbasins are relatively small basins with very limited storage. They are acutely sensitive and almost immediately affected by even small changes within the system. Several different attempts assuming no change in storage were made to obtain a set of conditioned heads for the transient model without success.

There are alternate methods for conditioning heads such as using dynamic cyclic initial conditions (Andersen and Woessner, 1992) or steady oscillatory conditions (Maddock and Vionnet, 1998) which both address seasonality averaged per month or per season. The latter method was tried but "averaging" heads created another set of problems, i.e., too much water in each microbasin for the beginning of the simulation period. An "averaged" set of heads was higher in elevation than water levels were in October 1997. Andersen and Woessner (1992) note that in some settings it may be inappropriate to assume steady-state conditions owing to large seasonal fluctuations in water levels. In this case the model may be calibrated to transient conditions. This alternative involves obtaining a set of conditioned heads by running a transient simulation with a set of defined heads. The simulation is run until the model heads match the field-measured heads. The calibrated heads can then be used as starting heads in predictive scenarios (Watts, 1989). The justification for choosing this method of conditioning is the assumption that the influence of initial conditions diminishes as the simulation progresses, so that any errors associated with incorrect initial conditions will be negligible provided enough time has elapsed (Andersen and Woessner, 1992).

Two different methods were used to condition heads for the microbasin model transient simulation. In the younger alluvium, running the simulation until the model simulated heads match the field observed heads was the method used as described above. The calibration criteria for the younger alluvium was based on the ability of the model to simulate the field measured water levels at the end of the fifth year of the simulation. In the older alluvium and Nogales Formation, hydrographs show very little change over time in the observation wells suggesting a "steady state" condition. The model was run for 25 years while calibrating parameters (specific yield, storage coefficient, mountain front recharge and hydraulic conductivity) that would result in stable water levels and no change in storage.

Calibration Process

Several criteria were used to evaluate the success of the model calibration. These included comparing model-simulated final water levels to measured water levels, comparing model-simulated hydrographs with actual hydrographs, comparing model-generated volumetric water budgets with conceptual water budgets, and comparing the Stream-Routing package results to stream gaging data and conceptual estimates of infiltration. In addition, comparison of the microbasin outflow to the calibrated inflow of the NIWTP model was used as a measure of success.

The calibration process involved identifying areas within the model that did not adequately simulate observed field conditions and then modifying the model input data. The input data was modified in order to achieve a better match between the model calibrated results and observed field conditions. Data was modified in preferential order based upon the level of confidence of the original estimates. In general, estimates of hydrogeologic contacts between the older alluvium and the Nogales Formation were considered to be of least confidence due to the gradational nature of the geologic contact. Water level data were considered to be of most confidence. Refer to Table 7-a for a qualitative ranking of model input data confidence.

Model Input Data	
Water Level Elevation Data	Most Confident
Areal Distribution of Pumpage	•
Surface Water Flow Gaging Data	•
Evapotranspiration Estimates	•
Horizontal Hydraulic Conductivity	•
Storage Components	•
Vertical Hydraulic Conductivity	•
Boundary Fluxes	•
River Conductance	•
Hydrogeologic Contacts Between Older Alluvium and Nogales Formation	Least Confident

Table 7-a. Qualitative Level of Confidence Ranking of the Original Microbasin Area Model Input Data.

Transient-State Calibration Results

Younger Alluvium

The model simulates transient-state surface water and groundwater conditions between October 1997 and September 2002. The model generally simulates groundwater flow directions and water level elevations reasonably well in the younger alluvial aquifer for the calibration period. Comparing actual well hydrographs to model-simulated water levels was one criteria used to evaluate the success of the model calibration. The appendix contains hydrographs and maps of measured and model-simulated water levels superimposed for easy comparison. In the younger alluvial aquifer, model simulated water levels are generally within five feet or less of the field measured water levels with the exception of the well located in the Kino Springs microbasin D-24-15 06aad, 55-803465, where simulated seasonal drawdowns were not well represented. The well, D-24-15 18bad, in the Buena Vista microbasin immediately downstream (approximately one-half mile) of the model boundary cell where streamflow is applied also displayed somewhat higher water levels. At first glance simulated and observed hydrographs appear very similar, however on closer inspection it is apparent that water levels are controlled by the river elevation, i.e., the effects of the Stream-Routing package. This is verified by the presence of stream discharge in the zone budget file. Historically, depth-to-water is generally 10 feet below land surface and fluctuates only a few feet. One possible explanation may be that it is a result of the temporal distribution of flows imposed in the Stream-Routing package. It is not likely the result of the constant head boundary at the border as the well, D-24-15 18dcb, 55-626375, upstream of the flow input does not display this characteristic. However, water level measurements at the upstream well are not available for the entire simulation period. The continuous flow in the river results in the Buena Vista microbasin remaining nearly full during the majority of the simulation period and may contribute to the problems at the above mentioned well in the Kino Springs microbasin. Rediscretizing flows into smaller stress periods would likely improve this problem however; the existing number of stress periods (94) is already nearly impracticable. Adding further complexity to this model may not be the most appropriate solution considering its future use as a predictive tool. See discussion below regarding stress periods.

The Guevavi microbasin was also somewhat problematic, however water levels seem to calibrate fairly well. Simulated water levels begin deviating from the observed water levels near the end of the simulation period in 55-607491. The Guevavi area is very complicated geologically. The area is bounded by three very large faults; the Mount Benedict fault, a fault identified by Simons (1974) and Halpenny and Halpenny (1983) coinciding with Guevavi Wash and a suspected fault that runs parallel to Guevavi Wash toward the north where Cretaceous Salero Formation and Tertiary Nogales Formation are in contact unconformably. Calibration problems in this area may also be related to the addition of two new wells installed by the City of Nogales . The wells were installed in the fall of 1999 and were brought on line in July 2000.

Older Alluvium/Nogales Formation

Only six wells in the older alluvium and Nogales Formation were measured during the model simulation period October 1997 through September 2002. Four of the wells were only measured once with one being measured while pumping. The other two wells were measured four to five times each, some having been noted as recently pumped. In addition to the absence of measurements, aquifer specific water levels are unknown due to the ambiguous nature of drillers' logs, lack of logs, and multiple aquifer completion of the six wells. Water levels are considered composite. The calibration goal in the older alluvium and Nogales Formation consisted of honoring available aquifer test data and verifying that model-generated hydrographs did not significantly change over the modeling period as suggested by the limited historical data. Water levels measurements taken prior to the model simulation period (prior to October 1997) were used in some instances to assess overall reasonableness of the simulated water levels. These wells are identified in Figure 3-B.

Water Budget

The model generated volumetric water budget provides an independent check of the overall acceptability of the model solution (McDonald and Harbaugh, 1988). The final model-generated volumetric water budget is presented in Table 7-b. This water budget agrees reasonably well with the conceptual water budget developed for the area. The overall mass balance error for the 94 stress periods was .03%. Anderson and Woessner (1992) recommend a mass balance error less than .1%.

Simulated recharge from the main channel of the Santa Cruz River matches the long-term conceptual estimate reasonably well in 1998 and 1999 when the annual inflow at the gage was approximately 60% and 64% respectively, of the long-term median of 13,500 acre-feet per year. In 2000 and 2002, observed streamflow was far below normal, 17% and 6% respectively. The volume of main channel recharge is considerably lower as expected. In 2001, the annual streamflow was 290% of the long-term median. However, the major and extended flows occurred in the fall and winter of 2000 – 2001 when stresses on the system were low and very little storage space was available in the aquifer. Hence, most of the streamflow did not infiltrate and passed on through the microbasin area as surface water outflow.

There were some discrepancies in simulated pumpage and evapotranspiration. Pumpage is approximately 95% accounted for with the remaining 5% being attributed to normalizing pumpage over a monthly stress periods. Observed water levels tend to drop acutely when the system is highly stressed as it is during the summer months. Well operators are able to temporally regulate pumpage. In the model, the wells continue to pump at a normalized monthly rate sometimes with water levels near the bottom of a well's perforated interval. This results in less water being pumped out of the well than the pumping rate assigned to the model cell. The simulated evapotranspiration was approximately 60% of the conceptual estimates. Snyder and Williams (2000) note that many widely used models assume that riparian trees derive water principally from the saturated zone (McDonald and Harbaugh, 1988), and in their opinion is clearly an oversimplification. They found in their study on the San Pedro River that mesquite (*prosopis velutina*) and cottonwood (*populus fremontii*) receive a high proportion (approximately 60% and 30% respectively) of transpiration water from shallow soil water after a rain event. Riparian stands along the Santa Cruz River are an integral part of the overall water management in the Santa Cruz AMA. Many changes have occurred in the riparian community since the Department's survey in 1995 and may possibly be attributed to extended periods of low runoff and disease. Further investigation is recommended.

Simulated main channel underflow from Mexico was slightly lower than the conceptual estimate and may be the result of below average flow in the Santa Cruz River during most of the simulation period. Below average streamflow may contribute to lower water levels in Mexico and a flatter gradient along the model boundary. Main channel underflow out of the model area appears to be within the conceptual range with more underflow occurring in 2001 as would be expected. Underflow at Eagan Narrows, out of the model area, was an important target of the calibration, as the resulting volume would be considered inflow to the NIWTP model. Independent calibrated values in both models are in agreement.

Annual Water Budgets Water Years 1998 through 2002 (acre-feet)

	Conceptual WY 1998	Model Estimate	Conceptual WY 1999	Model Estimate	Conceptual WY 2000	Model Estimate	Conceptual WY 2001	Model Estimate	Conceptual WY 2002	Model Estimate
GROUNDWATER IN										
Recharge										
Main Channel	5,720-8,580[1]	6,280	5,720-8,580[1]	4,530	5,720-8,580[1]	2,350	5,720-8,580[1]	4,530	5,720-8,580[1]	950
Mountain Front	1,370	1,170	1,370	1,1900	1,370	1,250	1,370	1,270	1,370	1,040
Underflow										
Main Channel	400-600[1]	400	400-600[1]	300	400-600[1]	420	400-600[1]	360	400-600[1]	360
Total Groundwater In	**5,900-8,260**	**7,850**	**5,900-8,260**	**6,020**	**5,900-8,260**	**4,020**	**5,900-8,260**	**6,160**	**5,900-8,260**	**2,350**
GROUNDWATER OUT										
Riparian	3,660	1,940	3,660	1,861	3,660	1,930	3,660	2,060	3,660	1,640
Pumpage										
Municipal	2,840		2,440		2,680		2,460		2,940	
Agricultural	360		360		300		220		150	
Other	110		120		110		120		140	
Total Pumpage	3,310	2,800	2,920	2,770	3,090	2,960	2,800	2,690	3,230	3,200
Underflow										
Main Channel	600-1,000[1]	1,000	600-1,000[1]	740	600-1,000[1]	940	600-1,000[1]	1,420	600-1,000[1]	560
Total Groundwater Out	**7,570-7,970**	**5,740**	**7,180-7,580**	**5,370**	**7,350-7,750**	**5,830**	**7,060-7,460**	**7,340**	**7,490-7,890**	**6,380**
Change-in-Storage		**2,110**		**650**		**1,810**		**1,180**		**-4,030**
SURFACE WATER IN										
Main Channel	8,030	8,030	8,440	8,440	2,290	2,290	38,580	38,580	820	820
Tributary	1,800	1,800	1,920	1,920	510	510	8,710	8,710	180	180
Total Surface Water In	**9,830**	**9,830**	**10,360**	**10,360**	**2,800**	**2,800**	**47,290**	**47,290**	**1,000**	**1,000**
Surface Water Out		**3,580**		**5,830**		**450**		**42,760**		**50**

Table 7-b. Conceptual and Model Simulated Annual Volumetric Water Budget for Water Years 1998 – 2002

[1]Estimate based on long-term annual average. Historical median flow in the Santa Cruz River is approximately 13,500 acre-feet per year. Surface water flows in to the study area were much less during study period except for water year 2000.

Change-in-storage results are reasonable. Note the change-in-storage occurs in 2001, a year with above average inflows. It might be expected that above average flows would result in an above average positive change-in-storage. As previously discussed, the majority of those flows occurred early in the water year, fall 2000 and winter 2001 when the system was already full. Storage was greatly affected in 2002 as would be expected. Very little surface water was available to replenish demands. Water levels at the end of the simulation confirm the loss of storage.

Stream-Routing Package

It was planned that comparing simulated stream leakage to field observed flow could be used as another tool for measuring the success of the calibration. This proved difficult in some respects, because there was no flow in the river during many of the field observations. The model simulations showed flow in the river on some of those occasions due to the normalization of flow over the entire length of a stress period. The total flow for a stress period was averaged as a constant per day rate for the stress period as is required by MODFLOW. When flow is imposed during a stress period, even a small amount, it obviously will not be able to match the intermittence of flow that was observed in the field at that particular time. The alternative would have been to more finely discretize time in the model. As discussed previously and later in this chapter, more stress periods are not feasible at this time.

One aspect of flow that was significant to the success of the model was to be able to simulate discharge at Guevavi Narrows particularly when there was no flow upstream as was observed in the field. The model was moderately successful with simulating this condition. In some instances discharge was simulated when there was none observed, however, the rate simulated by the model was usually between 0.1 to 0.2 cubic feet per second and may be considered negligible. The observation well immediately upstream of Guevavi Narrows, 55-619649 calibrates very well indicating that simulated water levels are fairly accurate. One explanation may be that the estimated riverbed (cell) elevation in the model could be slightly lower than the actual land surface elevation at Guevavi Narrows. Further investigation is recommended however; this situation serves to demonstrate the sensitivity of this model.

Further complicating calibration is the discrepancy between field observed flow and U.S. Geological Survey gage measured flow. Three of the 26 observations do not match the reported gage flow. In two instances the observed flow exceeded the gage-estimated flow by an order of magnitude. The input to the model was based on the gage-measured flow and therefore would not accurately match the observed flow in those stress periods. The U. S. Geological Survey records data from the gage frequently throughout the day. U.S. Geological Survey records were checked for the days where discrepancies existed looking for high flow periods (e.g., flash flood event) that would explain the difference in gage measurement and observation measurement. No evidence of high flows was recorded during those days. One explanation for the discrepancy could be the possible bifurcation of the stream channel. This would result in the flow being only partially recorded at the gage. Appendix C contains a table with the U.S. Geological Survey flow estimates, ADWR seepage run measurements, and the model simulated flow estimates.

Model Stability and Non-convergence

Model instability and non-convergence occurred frequently during the calibration process. Failure to converge occurs when the iterative solution of the groundwater flow equation does not meet the error criterion (a user specified value used to determine if the calculations have achieved an acceptable solution) within the maximum number of iterations specified. Failure to converge may be caused by many things including poor model conceptualization. According to Waterloo Hydrogeologic (2003), potential causes for failure to converge are: 1) oscillating cells converting between wet and dry; 2) sharp contrasts in hydraulic conductivity between adjacent cells; 3) lateral discontinuity (large changes in elevation) between cells in the same layer; and 4) active cells surrounded by dry cells. Each of these conditions may have occurred at one time or another during the model simulation. The small available storage space and high transmissivities leave the younger alluvium vulnerable to seasonal stresses on the aquifer. These conditions naturally result in groundwater depletion as is evidenced by wells becoming dry especially during the summer months. Several different attempts were made to mitigate the instability associated with the oscillation of rewetting cells such as: reducing the wetting interval to fewer iterations; splitting well pumpage between cells; rewetting cells from the bottom only (when surrounded by active dry cells or inactive cells); and changing the "head value in dry cells" (in the rewetting option within Visual MODFLOW) to the cell bottom elevation as opposed to the default elevation of –1e30 **feet.**

Model stability may have been reduced due to the sharp contrasts in hydraulic conductivity of the younger alluvium. Sharp contrasts in hydraulic conductivity between adjacent cells resulted because Visual MODFLOW only allows for evapotranspiration cells in layer one. (Layer one represents the younger alluvium and is very limited in extent as seen in Figure 2-C.) Initially, layer one cells were assigned to areas identified by Simons (1974) where there was sufficient thickness. This involved "clipping" the edges of layer one slightly closer to the river than was shown on the Simons (1974) map. However, large riparian communities exist in some of the clipped areas of layer 1 and likely obtain water from the younger alluvial aquifer. In order to accommodate this limitation of Visual MODFLOW (only allowing the assignment of evapotranspiration to layer one), layer one was slightly expanded to accommodate the riparian area identified by Masek (1996) but were given layer two or older alluvium properties, e.g., lower permeabilities and smaller storage coefficients. It was important not to appreciably increase the total storage capacity of layer one but to be able to accommodate the phreatophyte use. Placing cells with layer two properties or older alluvium properties next to cells with layer one properties or younger alluvium properties is highly contrasting, however representative of conditions existing in the microbasins.

Different numerical solvers were also tested to improve model stability. Solvers such as the PCG2 solver and the WHS solver were tried, but the best results were obtained using the SIP solver. Time steps were also shortened within stress periods when the model encountered problems. This did alleviate some instability in critical areas during high stress situations during the calibration. After calibration all stress periods were standardized to 10 time steps per stress period.

Summary

The model was calibrated for transient-state groundwater and surface water flow conditions. The calibration process consisted of identifying “poor calibration areas” and modifying the original input data. The success of the model calibration was evaluated by comparing the measured final water levels and the simulated final water levels, hydrographs of measured water level data for selected wells were compared to time varying model simulated water level data. Model-generated volumetric water budgets were compared to conceptual estimates, and output from the Stream-Routing package, simulated Santa Cruz River flow, was compared to conceptual estimates of measured streamflow.

Younger Alluvium

The success of the model simulation was based upon comparisons of model-simulated water levels throughout the model area for the younger alluvial aquifer, the older alluvial and Nogales Formation aquifers. The model simulated younger alluvial aquifer water levels and hydrographs compare relatively well. See Figure 7-? for simulated water levels and measured observation points. The mean absolute residual between the simulated and observed water levels in the younger alluvium is 4.6 feet. The mean absolute residual measures the average magnitude of the residuals and is calculated as follows. See Table 7-d for individual well statistics.

$$\left|\overline{R}\right| = \sum_{i=1}^{n} \left|R_i\right|$$

The normalized root mean square (RMS) error is also presented. It is a more representative measure of the fit than the standard RMS error because it accounts for the scale of the potential range of data values (Waterloo Hydrogeologic, Inc., 2004). The normalized RMS error is calculated by dividing the RMS error by the maximum difference in the observed head values. The normalized RMS for the younger alluvium is 2.8% indicating an acceptable calibration.

$$NormalizedRMS = \frac{RMS}{(X_{obs})_{\max} - (X_{obs})_{\min}}$$

Where: $(X_{obs})_{min}$ = minimum observed water level.

$(X_{obs})_{max}$ = maximum observed water level.

The correlation coefficient of .997 indicates that the simulated aquifer behavior matches the observed aquifer behavior in that when water levels drop or rise the simulation replicates the changes well. The correlation coefficient is calculated as the covariance between the calculated results and the observed results at select data points divided by the product of their standard deviations (Waterloo Hydrogeologic, Inc., 2004) .

$$Cor(X_{cal}, X_{obs}) = \frac{Cov(X_{cal}, X_{obs})}{\sigma_{cal} \cdot \sigma_{obs}}$$

Where: Cor = correlation coefficient
Cov = covariance
• = standard deviation
(X_{obs}) = observed water level
(X_{cal}) = calculated water level

Calibration Statistics for Individual Wells in the Younger Alluvium					
Observation Wells	**ADWR Registration No.**	**Number of Data Points**	**Absolute Residual Mean (feet)**	**Normalized Root Mean Square Error (%)**	**Correlation Coefficient**
D-23-14 15CCB1	55-607491	41	6.8	48.5	.77
D-23-14 16BCC	55-619649	60	2.5	43.0	.32
D-23-14 25CDB		20	9.1	24.5	.98
D-23-14 27ADD	55-619646	47	4.4	17.8	.91
D-23-14 36BCB1	55-603439	17	5.2	13.4	.88
D-23-15 31CAC	55-625359	37	5.6	22.2	.91
D-24-15 06AAD	55-803465	58	5.6	25.3	.89
D-24-15 18BAD UNSURV		49	2.7	41.8	.60
D-24-15 18DCB UNSURV	55-626375	13	2.2	82.8	-0.17

Table 7-c. Table showing Calibration Statistics for Individual Wells in the Younger Alluvium.

The residual distribution histogram provides a qualitative comparison of the distribution of the normalized calibration residual values against the norm distribution curve. Ideally, the distribution of the calibration residual of a large number of observation points would be similar to the that of the normal distribution curve, with most of the residual groups clustered around the value of zero (Waterloo Hydrogeologic, Inc., 2004). Figure 7-A shows the population and frequency of observations for specified intervals of the normalized calibration residual values for the younger alluvium.

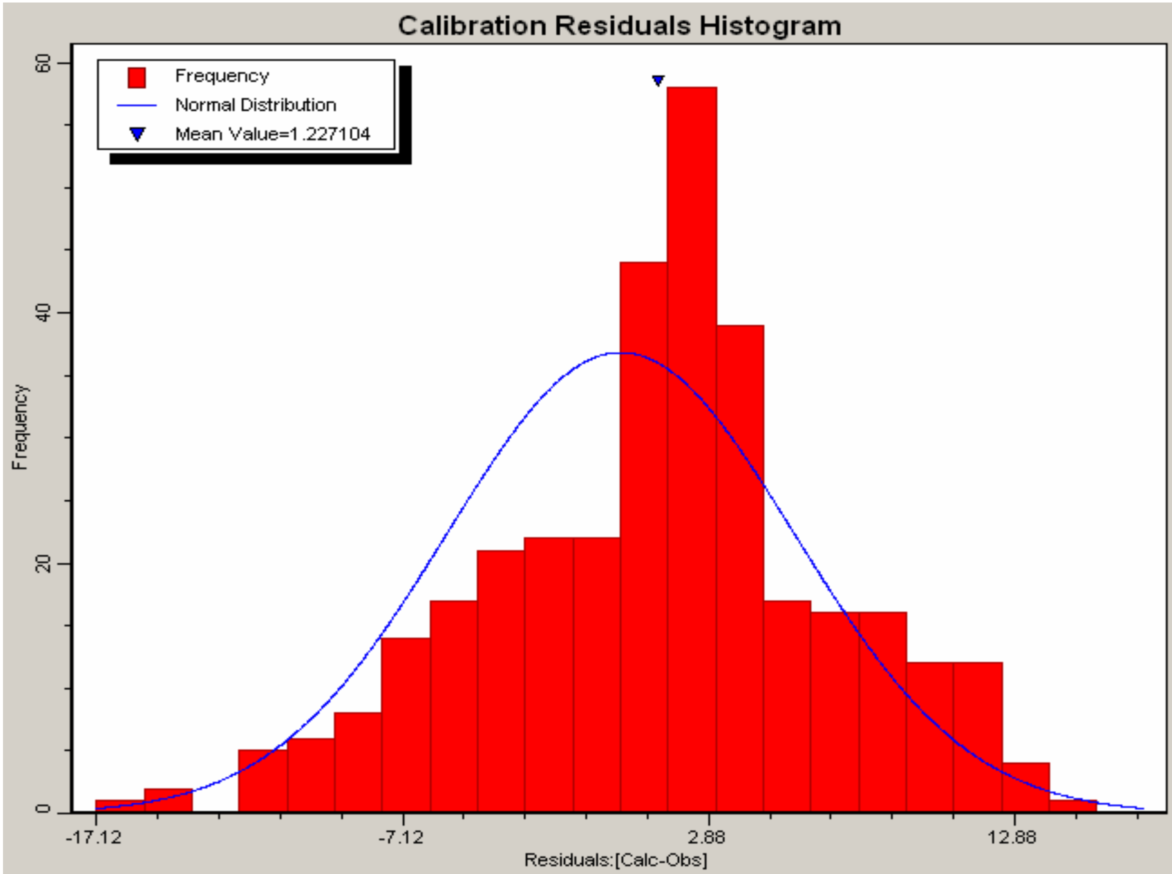

Figure 7-A. Calibration Residuals Histogram for the Younger Alluvium.

Figure 7-B is a scatter graph of calculated water levels versus observed water levels. This graph represents a snap-shot in time of the comparison between the values calculated by the model and the values observed in the field (Waterloo Hydrogeologic, Inc., 2004). Ideally, all of the points should intersect the solid blue line however, this would rarely occur in reality. Data points that occur over the line indicate the model is over-predicting water levels and data points under the line indicate the model is under-predicting water levels. The dashed blue lines represent the 95% confidence interval. This interval allows the user to visualize a range of calculated values for each observed value with 95 % confidence that the simulation results will be acceptable for a given value. The majority of the simulated values for this model fall within the 95% confidence interval. The goal for the model calibration should be to have the 45 degree line where X=Y fall within the 95% confidence interval lines which it does (Waterloo Hydrogeologic, Inc., 2004). The dashed red line is the 95% interval where 95% of data points are expected to occur.

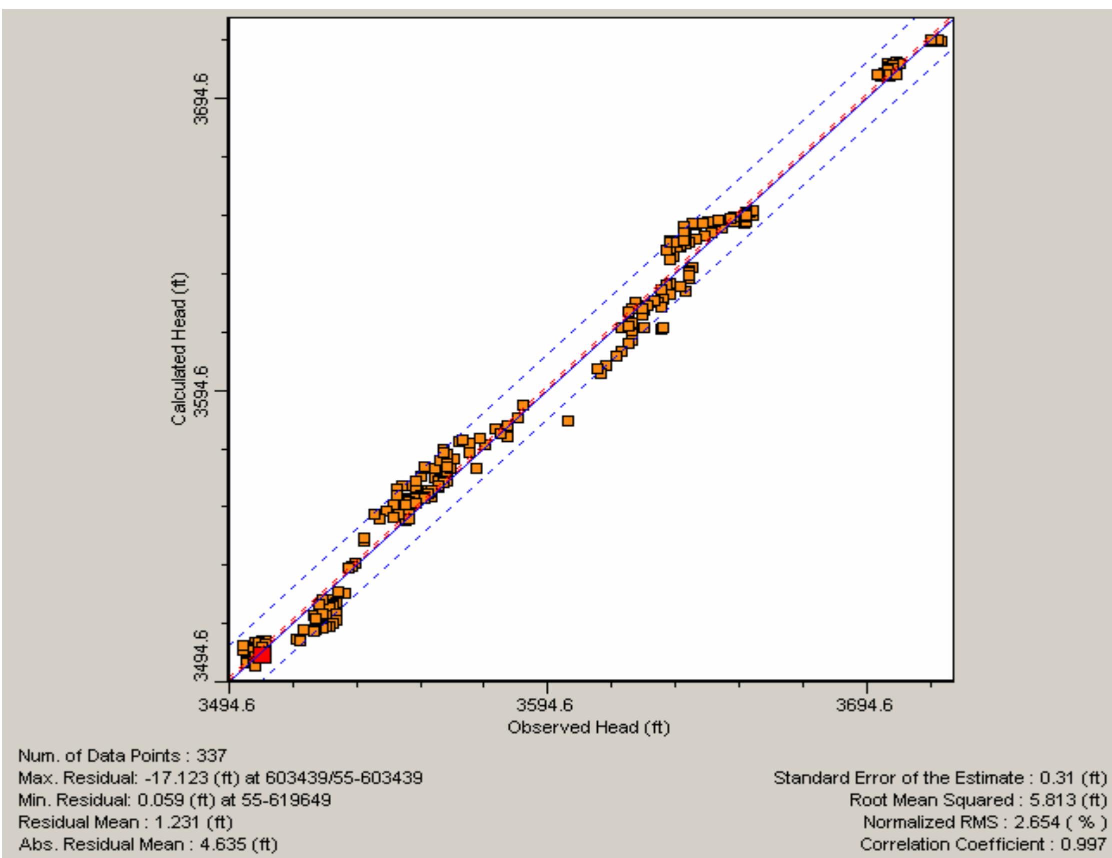

Figure 7-B. Scatter Graph of Younger Alluvium Residuals.

Older Alluvium and Nogales Formation

As discussed earlier the older alluvium and Nogales Formation calibration is tenuous. The lack of field observations does not lend itself to a statistical analysis and inherently results in low confidence. Table 7-d presents residuals for the wells that only have one data point and mean absolute residuals for wells with more than one data point.

Residuals for Individual Wells in the Older Alluvium			
Observation Wells	**ADWR Registration No.**	**Number of Data Points**	**Residual and mean absolute residual (feet)**
D-23-14S01ACA	55-534962	1	13.8
D-23-14 24DAC	55-635411	0[1]	.05
D-23-15 18ABA UNSURV		1	.5
D-23-15 19ABB	55-805426	4	7.9
D-24-15 04DDD1 UNSURV	55-625340	5	38.3
D-24-15 08ADD	55-625357	0[1]	10.3
D-24-15 08ADB UNSURV	55-511616	1	8.0
D-24-15 08ADC UNSURV	55-510018	0[1]	5.2
D-24-15 15CDB	55-626377	0[1]	11.1
D-24-15 16DBB UNSURV	55-626374	1	16.1

Table 7-d. Table showing Older Alluvium and Nogales Formation Residuals.

[1]These wells were not measured during the calibration period, however a data point was inserted in the model run based on prior measurements to use as a reference point in areas where there was little or no data.

The inability to calibrate the well 55-625340 is responsible for the large residual in Table 7-d. (This well is referred to in Chapter 3 – Hydrogeology. It is associated with the Kino Springs Village aquifer test and is most likely completed in fractured Nogales Formation.) Transmissivities may be simulated moderately well, but due to the lack of data available to define basin geometry and aquifer tests, aquifer parameters cannot be estimated with much confidence. Updating the model with recent water level measurements, expanding the number of wells monitored, acquiring more aquifer test data, and obtaining better definition of the hydrostratigraphic units are recommended to improve confidence in the results.

	Initial Average	***Calibrated Average***
Horizontal Hydraulic Conductivity		
Layer 1 - Yal		
Buena Vista	350 Ft/Day	350 Ft/Day
Kino Springs	600 Ft/Day	975 Ft/Day
Highway 82	600 Ft/Day	850 - 975 Ft/Day
Guevavi	500 Ft/Day	550 Ft/Day
Layer 2		
Oal - Southern Area	0.3 Ft/Day	.19 – 1.1 Ft/Day
Oal - Central Area	0.3 Ft/Day	.85 Ft/Day
Salero Formation	5 - 35 Ft/Day	3.0 Ft/Day
Layer 3 – Nogales Fm.	.4 - .5 Ft/Day	.19 Ft/Day
Specific Yield		
Layer 1 - Yal		
Buena Vista	.14 - .17	.14
Kino Springs	.14 - .20	.14
Highway 82	.14 - .20	.14
Guevavi	.14 - .20	.14
Layer 2 - Oal	.0014 - .0001	.025
Salero Formation	.1 - .15	.15
Layer 3 – Nogales Fm.	.00011	.0001
Specific Storage		
	Storage Coefficient	Specific Storage (1/feet)
Layer 1 - Yal	N/A	N/A
Layer 2 - Oal	.0014 - .0001	3.5e-6
Salero Formation	.1 - .15	.0005
Layer 3 – Nogales Fm.	.00011	6.67e-6

Table 7-e. Table showing Calibrated Values of Hydraulic Parameters.

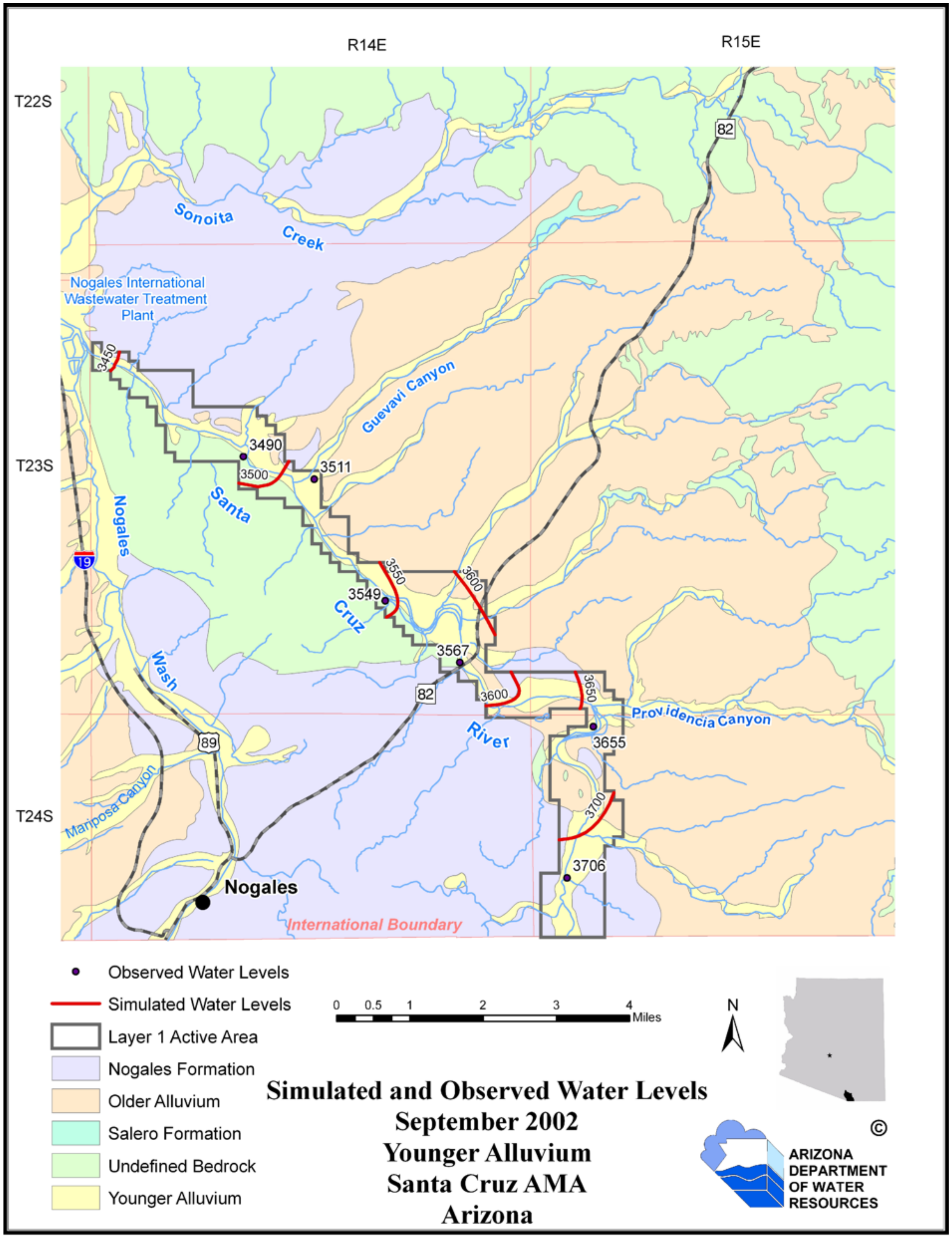

Figure 7-C. **Map showing Simulated and Observed Water Levels in the Younger Alluvium at the end of the Study Period.**

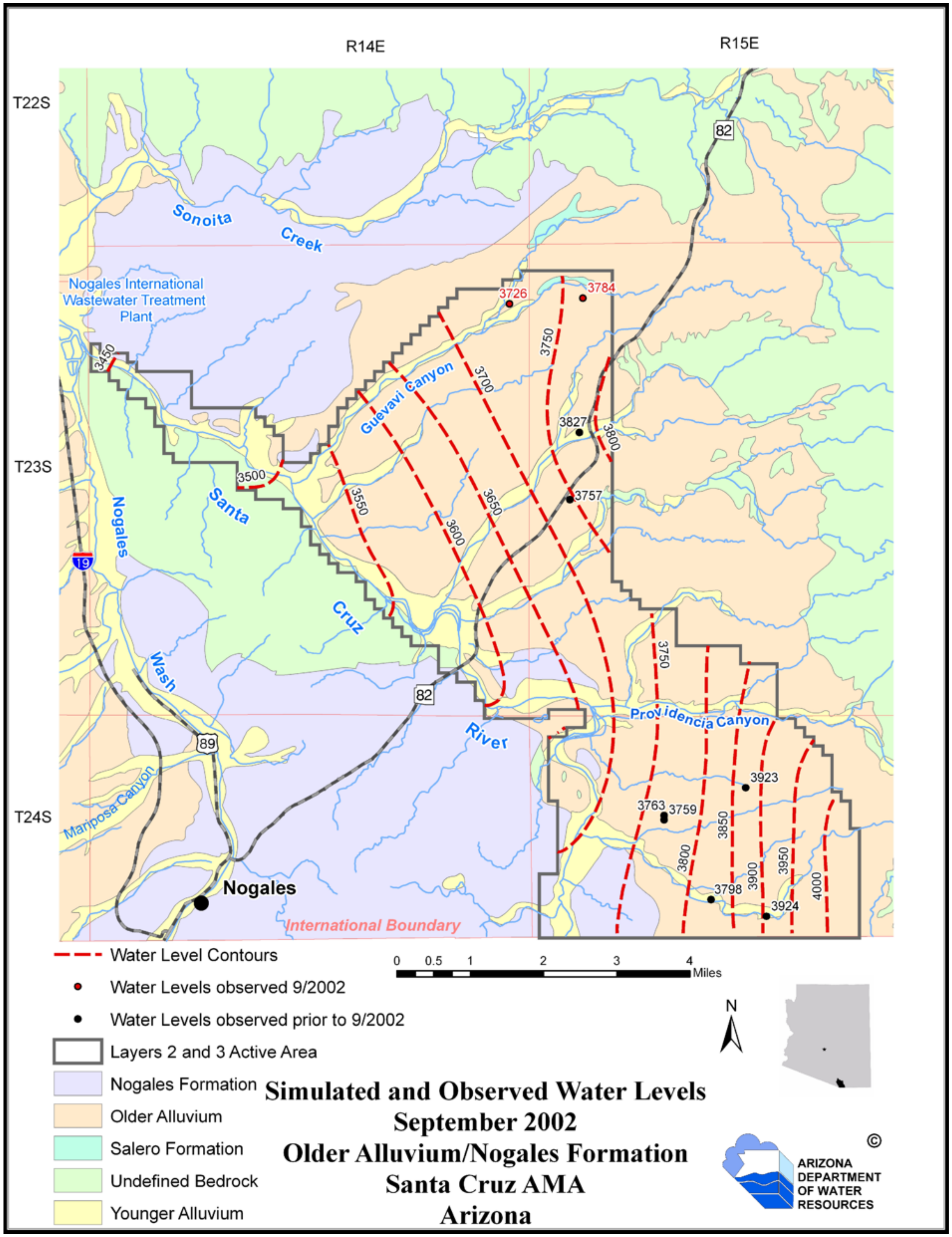

Figure 7-D. **Map showing Simulated and Observed Water Levels in the Older Alluvium and Nogales Formation at the end of the Study Period.**

Chapter 8 - Sensitivity Analysis

A sensitivity analysis was conducted to determine how sensitive the model solution is to uncertainty in each input component. As is generally the case with numerical models, uncertainty exists with the original data and not all of the input components were known with great confidence. The purpose of a sensitivity analysis is to determine which input components exert the most control over the model solution and, therefore could generate the largest potential errors. An improved understanding (i.e., reduction of the uncertainty) of the most influential input components would yield the greatest improvement for future model inputs.

The usual procedure in a traditional sensitivity analysis is to test the sensitivity of the model by changing a single input component over a reasonable range of values during a series of model runs. This procedure was attempted with very limited success due to the instability of the younger alluvial aquifer. The input components that were changed included hydraulic conductivity and boundary conditions. These components were selected since they are major input variables of the model. In the traditional type sensitivity analysis a parameter is usually changed over a large scale such as two to five times the original value. In the microbasin model small changes, sometimes as little as 10% could result in non-convergence. Larger changes could be tolerated in the older alluvium and Nogales Formation. Prior to the traditional sensitivity analysis parameter estimation was attempted using Visual MODFLOW's WinPEST, parameter estimation package. Not surprisingly, parameter estimation failed due to the model's stability problems. If WinPEST chose a parameter that was too dissimilar from the original input value the run would fail to converge and stop the estimation process.

Three statistical measures were used to evaluate the model sensitivity. Two measures are the mean absolute residual and normalized root mean square error of the water levels for each sensitivity simulation. The third measure was volumetric water budgets for each sensitivity run compared to the final calibrated water budget. Tables 8-a and 8-b compare the percent difference between the mean absolute residual and normalized root mean square error of water level changes within the selected areas and the percent change in storage from the final calibrated volumetric water budget.

Model Input Parameters	Younger Alluvium			Older Alluvium and Nogales Formation		
	Mean Absolute Residual	Normalized Root Mean Square Error	Correlation Coefficient	Mean Absolute Residual	Normalized Root Mean Square Error	Correlation Coefficient
Transmissivity						
Decrease in Transmissivity x50%	NC	NC	NC	NC	NC	NC
Increase in Transmissivity x2	NC	NC	NC	NC	NC	NC
Horizontal Hydraulic Conductivity (K) and Vertical Conductivity						
Increase K 10% [1]	+.036	+.008	0	NA	NA	NA
Increase K 25%	+.972	+.193	-.001	NA	NA	NA
Increase K 50%	NC	NC	NC	+2.531	+.137	-.004
Increase K x2	NA	NA	NA	+5.041	+2.148	-.009
Increase K x5	NA	NA	NA	NC	NC	NC
Decrease K 10%[2]	-.03	-.03	0	-.399	-.171	+.001
Decrease K 20%[2]	-.07	-.056	0	NA	NA	NA
Decrease K 25%	NC	NC	NC	NC	NC	NC
Decrease K 50%	NA	NA	NA	NC	NC	NC
Specific Yield and Storage Coefficient						
Increase Sy or Sc x2	-.37	-.25	-.001	NA	NA	NA
Increase Sy or Sc x5	NA	NA	NA	+1.158	+5.174	-.012
Decrease Sy or Sc 25%	NC	NC	NC	NA	NA	NA
Decrease Sy or Sc 50%	NC	NC	NC	NC	NC	NC

Table 8-a. Summary of Sensitivity Statistical Analysis – Hydraulic Parameters

Sensitivity simulation statistics minus calibrated simulation statistics.

Note: All differences are changes between the calibrated water levels or water budget components and the sensitivity run.
NC – Failed to converge.
NA – Parameter was not tested.
[1]Failed to converge in Guevavi microbasin. Guevavi remained at calibrated value. All others increased by 10%.
[2]Failed to converge in Kino Springs/Highway 82 microbasin. Remained at calibrated value while decreasing all others by 10%.
Spell out model input components or make a legend below table.

Model Input Parameters	Younger Alluvium			Older Alluvium and Nogales Formation		
	Absolute Residual Mean	Normalized Root Mean Squared	Correlation Coefficient	Absolute Residual Mean	Normalized Root Mean Squared	Correlation Coefficient
Phreatophyte Use / Evapotranspiration						
Increase ET 25%	+.077	+3.51	0	NA	NA	NA
Increase ET 50%	NC	NC	NC	NA	NA	NA
Decrease ET 25%	-.132	-.098	0	NA	NA	NA
Decrease ET 33%	NC	NC	NC	NA	NA	NA
Decrease ET 50%	NC	NC	NC	NA	NA	NA
Stream Conductance						
Decrease Stream Conductance x50%	NC	NC	NC	NA	NA	NA
Increase Stream Conductance x2	NC	NC	NC	NA	NA	NA
Mountain Front Recharge						
Increase Recharge x5	-.003	-.003	0	+14.063	+8.973	-.092
Decrease Recharge x5	+.001	0	0	+4.379	+1.609	-.007

Table 8-b. Summary of Sensitivity Statistical Analysis – Boundary Conditions.

Sensitivity simulation statistics minus calibrated simulation statistics.
Note: All differences are changes between the calibrated water levels or water budget components and the sensitivity run.
NC – Failed to converge.
NA – Parameter was not tested.

Increasing the transmissivity by a factor of two and cutting transmissivity by 50% both resulted in non-convergence in layers 1 and 2. Generally layer one is most sensitive and non-convergence problems will occur near the City of Nogales' wellfield in the Kino Springs and Highway 82 microbasins. In order to test transmissivity in layers two and three, layer one was left unchanged. Non-convergence occurred in layer two in the above-mentioned location.

The younger alluvium became unstable with any substantial changes in horizontal and vertical hydraulic conductivity. Table 8-a shows values could only be changed by 20-25% without resulting in non-convergence. The simulations that did converge had only minor effects on water levels. A larger increase in horizontal and vertical hydraulic conductivity was more successful in the older alluvium and Nogales Formation. Increasing the parameter by a factor of five resulted with water levels lowering and the absolute residual mean being increased by five feet, a 40% increase over the calibrated value. Decreasing hydraulic conductivity in the older alluvium and Nogales Formation was not as successful. A change of only 10% could be made without convergence problems. Water levels were scarcely affected.

Decreasing specific yield in the younger alluvium and older alluvium and the storage coefficient in the Nogales Formation resulted in non-convergence of the model solution. Increasing the specific yield in the younger alluvium by two did not affect the model solution noticeably. It resulted in a change-in-storage of 8%. Increasing the specific yield and storage coefficient in the older alluvium and Nogales Formation respectively, increased the normalized root mean squared from 6.18% to 11.36% and increased the absolute residual mean by approximately one foot. It resulted in no overall change-in-storage.

Increasing or decreasing evapotranspiration by 25% produced little change in the absolute residual mean, less than approximately one-tenth of a foot. When there was a greater change in the parameter, 33% decrease and a 50% increase in the rate, the model became unstable and did not converge.

Stream conductance was increased by 100% and decreased by 50%. Both runs resulted in non-convergence. Further analysis is recommended.

Mountain front recharge was increased and decreased by a factor of five. Mountain front recharge is applied in layer two and as can be seen by the results, has almost no effect on the younger alluvium. Increasing recharge increased the absolute residual mean by 14 feet and predictably raised water levels. Decreasing recharge increased the absolute residual mean by approximately four feet and resulted in declining water levels.

Sensitivity Analysis Summary

The sensitivity analysis was not very successful in the microbasin model due to the instability problems in the younger alluvial aquifer. Even changes in the older alluvium and Nogales Formation at times affected stability in the younger alluvium The limited data shows the model is not very sensitive to small changes in the hydraulic parameters and boundary conditions and the changes do not appear to affect the overall error to any great degree. The results indicate that a small range of values exist for most of the parameter values, generally + or – 10% of the calibrated value.

Better results might be obtained if changes were coordinated in two or more parameter values. For example, hydraulic conductivity and areal recharge may be both increased and hydraulic heads may change very little. This type of sensitivity analysis may mitigate some of the instability when parameters are changed and provide a more valuable analysis. Future recommendations include this type of sensitivity analysis.

Stress Period Sensitivity Analysis

The length of stress periods is an important factor in the success of the calibration. Originally the seasonal stress periods were set up using five stress periods per year (two to three months long each.) This time discretization required that the streamflow be averaged resulting in flow occurring over the entire stress period, i.e., flow in the river all year long. Simulated streamflow in the river all year long resulted in constant simulated recharge to the younger alluvial aquifer, which proved to be detrimental to the calibration. The acute declines in observed water levels could not be replicated with a constant source of recharge available. The importance of simulating periods of no flow and high flow were necessary to a successful calibration and replication of observed water level fluctuations. Stress period dates and days are in Appendix A.

In order to minimize the detrimental effects of averaged streamflow, the microbasin model was run for the 5-year calibration period from October 1, 1997 through November 30, 2002 using 94 stress periods. Stream package stress periods were determined by identifying the significant events (dry or wet) in the river as recorded at the U.S. Geological Survey gage 09480500, Santa Cruz River near Nogales. Visual MODFLOW automatically determined the minimum number of stress periods necessary to accommodate a variety of different stresses (e.g., evapotranspiration, streamflow, pumpage, recharge, etc.). Distinct streamflow events accounted for 43 stress periods during the 5-year calibration period. Stress periods ranged from one day to 273 days in length. Most other data such as pumpage and evapotranspiration were accounted for on a monthly basis. Mountain front recharge was uniformly applied over the model simulation period. The 43 stress periods for the stream package and 60 for other data resulted in 94 stress periods overall.

Stress period length was varied for the sensitivity analysis. Monthly and semi-monthly stress periods were used to test whether a longer stress period length would negatively affect model results. The results of the test were inconclusive. Differences between 94 stress periods, monthly (60) stress periods and semi-monthly (78 – see note at end) stress periods were minimal. Stream recharge increased only slightly (approximately 2%). One possible explanation for this may be the assignment of the stream stage or conductance term; specifically the assignment of stream top, stream bottom, width and streambed conductivity during various flow magnitudes and durations. Criteria were set up for the assignment of the conductance term for flows of various magnitudes and durations in the 94 stress period simulations. The same criteria were used for assignment of the conductance term in the monthly and semi-monthly stress period simulations. The minimal differences in recharge between the simulations may indicate the need to revisit the criteria used in the initial conductance value determination. Another possible explanation could be that that a monthly stress period is a viable option. Figures 8-A and 8-B show that when there is aquifer storage space available the recharge rate can nearly equal the surface water inflow rate. However, at some point the rate of recharge maximizes regardless of the magnitude of the flow as seen in the October 2000 event. (See Figure 8-B for duration and magnitude.)

Correlations between Flow Magnitude, Duration, and Recharge

Figures 8-A and 8-B illustrate surface water inflow and model simulated recharge. Figure 8-A shows the total volume of surface water inflow per stress period and the model simulated volume of recharge. It also shows water levels in the Kino Springs microbasin. Figure 8-B shows the rate of inflow per stress period and the rate of recharge. The simulated recharge volume and rate were obtained from the modflow.lst or list file.

The figures indicate the importance of antecedent conditions. If the microbasins are full prior to a flow event, relatively little recharge occurs. In addition, the figures show that there is a seasonal component to the recharge. The troughs in the water level hydrograph generally coincide with summer seasons. In the summer, when evapotranspiration and pumping are high, there is typically more storage space available in the aquifer and therefore a greater percentage of surface flow recharges than during other times of the year. This statement only applies to the study period. Data is not available to make this conclusion for the historical record.

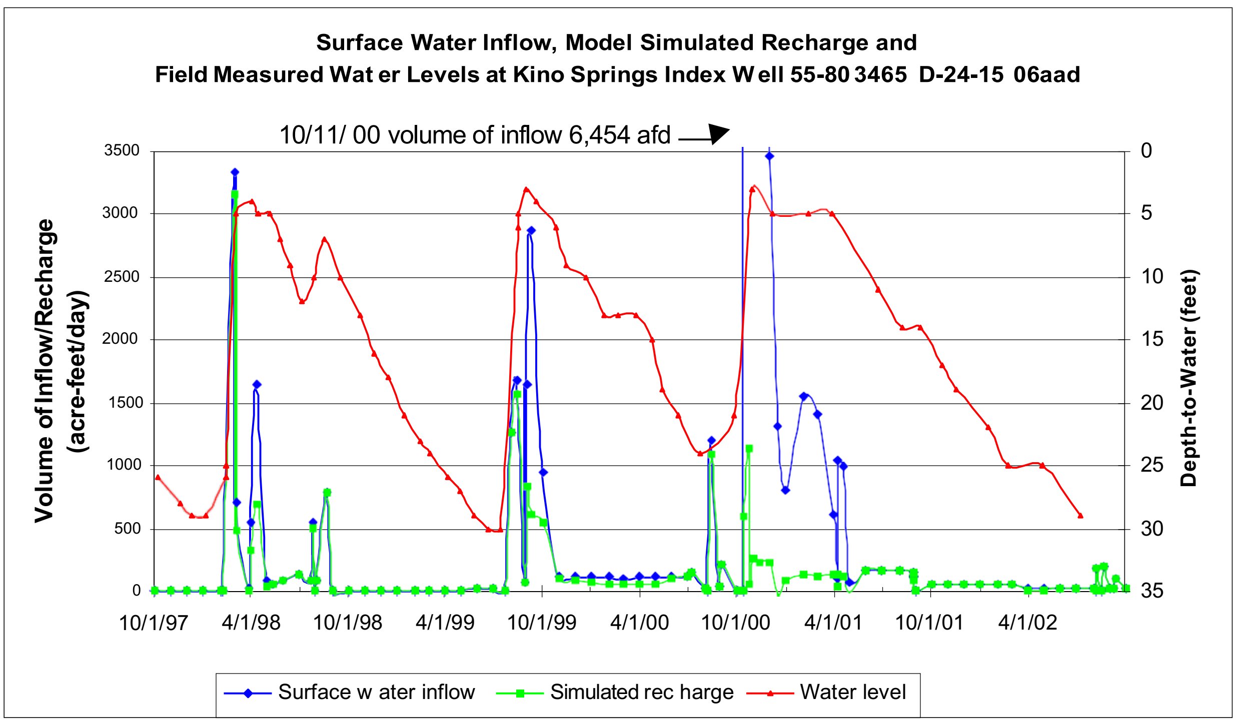

Figure 8-A. **Santa Cruz River Inflow at Gage 09480500, Simulated Recharge and Kino Springs Microbasin Water Levels – 10/1997 through 9/2002.**

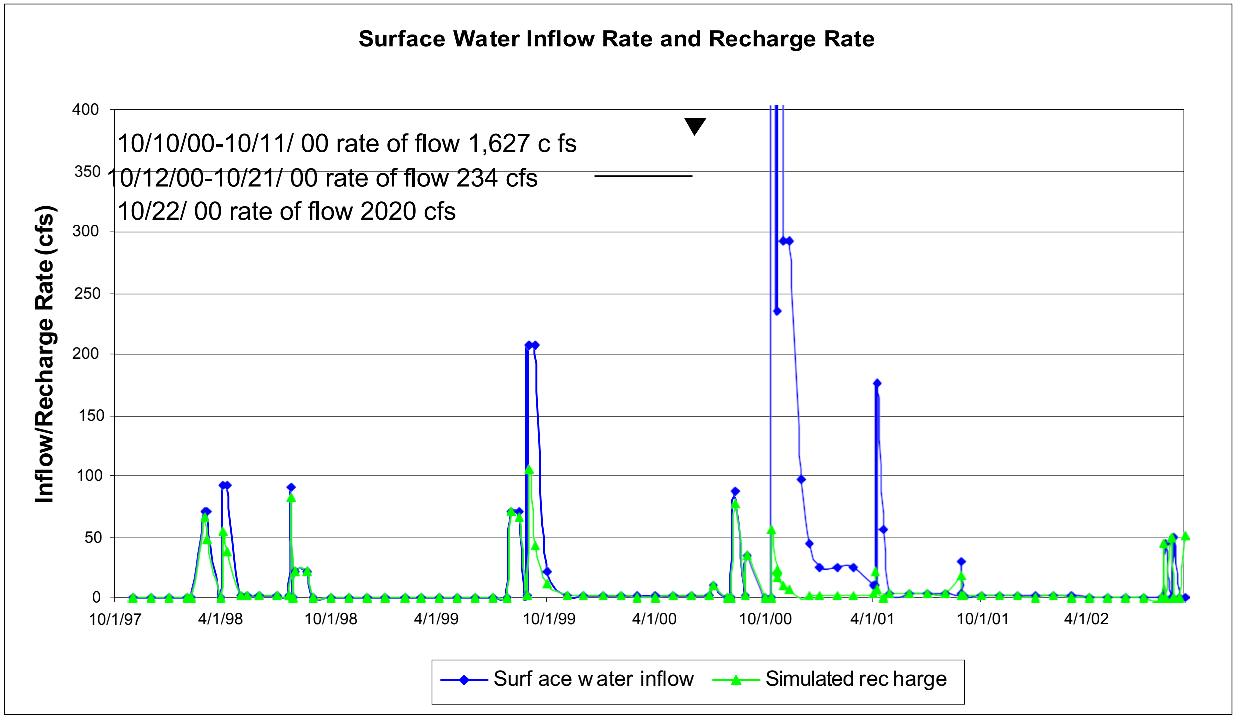

Figure 8-B. **Santa Cruz River Inflow Rate and Recharge Rate – 10/1997 through 9/2002**

It is difficult to make correlations between magnitude, duration and rate or volume of recharge because of antecedent conditions. However, some preliminary conclusions were made in the table below. (It is recommended that correlations between magnitude, duration, recharge and antecedent conditions be further analyzed.) In addition to the effects of antecedent conditions, the data below are also affected by averaging flow over a stress period. Model stress periods that averaged flows greater than 50 cfs accounted for a longer period of time than the actual historical record indicated. Flows exceeded 50 cfs on 147 days in the model simulation. According to the historical record the actual time average daily flows exceeded 50 cfs was 112 days.

Approximately one-half (53%) of the total volume of simulated surface water recharge occurs over a relatively short amount of time, 100 days (5.5% of total model days) from flows ranging between 50 and 100 cfs. The remaining recharge can be divided into flows less than 50 cfs and flows greater than 100 cfs. Flows greater than 100 cfs occurred only 47 days (2.5% of total model days) and contributed 19% (3,633 AF) of the total volume of simulated recharge. Flows less than 50 cfs occurred over 1678 days (92% of the total model days) and accounts for 28%

(5223 AF) of the total volume of recharge. Note that for approximately one-half of the model run (970 days = 53%) the average flow in the river was < 1 cfs and contributed only 514 AF, or 3% of the total recharge.

Stress Period average flow at gage 09480500* cfs	Number of stress periods during 5-year simulation period 94 stress periods	Total number of days during 5-year simulation period 1825 days	Actual Days in U.S. Geological Survey record 1826 days	Total volume of simulated recharge 18,664 AF	Percent of total simulated recharge
< 50	75	1678	1714	5223	28%
50 – 100	11	100	44	9808	53%
> 100	8	47	68	3633	19%

Table 8-c. Relationship between Inflow Rates and Recharge.

* Does not include tributary inflow

Table 8-d was prepared to determine if flows of a specified magnitude or range could be assumed to fully recharge. If an obvious relationship existed it would allow for more emphasis on the frequency of flows of a higher magnitude in the flow frequency projections. The same analysis was done for flows less than or equal to 25 cfs and flows less than and equal to 10 cfs. Both had similar results to the 50 cfs analysis. Two factors were not addressed in this analysis: 1) wet antecedent conditions, and 2) stress period duration. Further analysis with these considerations is suggested.

Number of stress periods that fall within the flow range 75 total stress periods	**Percentage of surface water inflow that recharges when flows are <= 50 cfs**	**Total number of days when percentage of inflow recharged** Flow <= 50 cfs 1678 days
11	100	118
18	90-99	424
9	80-89	228
4	70-79	122
5	60-69	106
3	50-59	63
2	40-49	54
4	30-39	110
3	20-29	67
1	10-19	30
3	1-9	75
12	0	281

Table 8-d. Percentage of Flows that Recharge when Stress Period Flows are less than or equal to 50 cfs.

Table 8-d shows approximately 37% (or 29 of the 75 stress periods) of flows that are less than or equal to 50 cfs fully recharge. (For the purposes of this analysis, anything over 90% recharged is considered to fully recharge because surface water outflow is negligible. Eight of the 18 stress periods in the 90-99% infiltration range exceeded 97%.) In the stress periods when no recharge occurs, nine of the 12 stress periods had no flow in the river during that time. The other three stress periods with no recharge can be attributed to wet antecedent conditions where little or no aquifer storage space was available. These relations apply only to the modeled period (water years 1998-2002), so general relations about historical streamflow and recharge can not be inferred.

Stress Period Sensitivity Analysis Summary

- Monthly stress periods may work well enough for the flow frequency projections as long as there are stress periods when there is no flow or very little flow.

- During “wet year” projections, it may be necessary to shorten some of the summer stress periods to allow for stress periods with no flow.
- Values used in the stream-flow routing package such as stream stage, streambed conductivity and stream width need to be further tested.
- Model results indicate the recharge rate can nearly equal the inflow rate when there is storage available in the aquifer.
- Lower flows of a longer duration are probably more critical to the analysis than flows of a high magnitude. The recharge rate maximizes, at some point (when the aquifer is full), regardless of the magnitude of the flow.
- Correlations between flow magnitude, duration and recharge are difficult to make without considering antecedent conditions. Further analysis is suggested.
- The model simulation period of October 1997 through September 2002 is one of the driest periods on record and is not representative of the historical record. The five-year simulation should not be used to predict future “average” conditions using the current flow regime.

Note regarding semi-monthly stress periods: There were times throughout the model simulation when consecutive semi-monthly stress periods had the same average flow. Those periods were grouped together in the stream package, e.g., days 365-488 had the same average rate of zero cfs. For simplicity, it was entered in the stream package as days 365-488 at zero cfs rather than eight consecutive stress periods at zero cfs. Visual MODFLOW determines the minimum number of stress periods necessary to represent all of the data. Hence, the minimum number of stress periods needed to represent the data was 78 as opposed to 120 which would have occurred had the data been entered in semi-monthly increments in the stream package.

Chapter 9 - Conclusions and Recommendations

Conclusions

Younger Alluvium

In general, the groundwater flow model developed for the Santa Cruz River microbasins appears to reasonably simulate groundwater conditions in the younger alluvial aquifer. However, aquifer parameters, could not be rigorously tested for their sensitivity due to stability problems with the model. Therefore, this particular solution should be considered non-unique. Other combinations of parameters and boundary conditions may also provide a viable solution, and it would be necessary to recalibrate the model to test these other combinations. However, it is important to recognize that the current model was developed using the current available data, and significantly different conceptual models would be based on even less certain data and assumptions.

The model is suitable for evaluating streamflow infiltration to the younger alluvial aquifer and thereby surface water outflow to the NIWTP model area for planning purposes. Stability problems for future runs could be problematic when running long-term predictive scenarios, particularly for scenarios that could simulate long periods of low flow in the Santa Cruz River with constant or increasing future pumping demands.

Specifically, the model indicated that the older alluvium and Nogales Formation contribute little water to the younger alluvial aquifer. The Buena Vista microbasin is recharged by underflow from Mexico and streamflow infiltration. The Kino Springs and Highway 82 microbasins are relatively isolated on both sides of the river and receive nearly all of their recharge from streamflow infiltration. The Guevavi microbasin receives some recharge from streamflow infiltration and from underflow via the Salero Formation.

Older Alluvium and Nogales Formation

The simulation of groundwater conditions in the older alluvium/Nogales Formation cannot be considered very reliable without more supporting data. The available data are generally insufficient to strongly support the modeling results. Many simplifying assumptions were made for an area that is quite complex both geologically and hydrologically. For example, it has been suggested that groundwater flow in the older alluvium and Nogales Formation are controlled by fractures and faulting (Halpenny, 1963; Halpenny and Halpenny, 1991; and Gettings and Houser, 1997). The conceptual model used in the microbasin model assumed groundwater flow in the older alluvium and Nogales Formation occurs through a continuous porous medium that may be an over-simplification that would have been better simulated using a different governing equation than the general saturated flow equation utilized by MODFLOW. Forming a conceptual model of a fractured system requires either a gross simplification or a detailed description of the aquifer properties controlling flow (Andersen and Woessner, 1992). Since no information was available describing the fracture apertures, lengths, and interconnections as well as the identification of any of the associated hydraulic parameters the simplified conceptual model was necessary. It should be noted that many models have been successfully developed that simulate fracture or preferential flow on a regional scale using MODFLOW. However, there is lower confidence in the results of the older alluvium and Nogales Formation calibration and future predictive scenarios should take these concerns into account.

Recommendations

1. Periodically update the model with new data as it becomes available to improve the model calibration for use as a planning tool.
2. The younger alluvial aquifer may be better modeled using a more refined spatial distribution, i.e., smaller cell size.
3. Investigate the use of a different type of model or newly updated MODFLOW packages (e.g., Stream-Routing Package updates SFR1 and SFR2) to better simulate the highly variable conditions that exists in the younger alluvial aquifer.

4. Obtain specific pumpage data from Mexico. This would help in understanding hydrologic conditions in Mexico and help quantify the effects of the pumpage with regards to surface water flowing into the United States from Mexico.
5. Continue acquisition of new field data. More groundwater level data in the older alluvial and Nogales Formation aquifers are needed as well as more information on aquifer thickness, aquifer boundaries, and hydraulic properties. Temporal data in the younger alluvial aquifer is particularly useful to insure a good calibration.
6. Mountain front recharge estimates should be studied and improved with new data collection.
7. Update riparian distributions and types due to changing conditions.
8. Design a data collection program to gather data for estimating stream infiltration including additional stream gages, monitoring wells, and stage recorders as well as the collection of temperature data from monitor wells and the Santa Cruz River.

Model Reliability

There are several factors that affect the reliability of the numerical model constructed for the microbasin area in Santa Cruz Active Management Area. These factors must be considered when evaluating the calibration results or utilizing the model for predictive scenarios. The factors include the level of uncertainty of the original input data, the analysis of the calibrated error between model simulated and measured water levels, and the sensitivity of certain model input parameters and their influence on the accuracy of the model solution. In conjunction with these factors, certain simplifying assumptions were necessary to represent the conceptual model of the groundwater flow system within the framework of the numerical model. Most of the assumptions used to develop the model have been fully discussed and justified previously. However, it is important to understand these assumptions when evaluating the reliability and limitations of the model. The primary assumptions are:

1. Water levels in all model layers (i.e., all hydrogeologic units) were initially assumed to be identical in elevation. This hydraulic condition may not have accurately simulated the three dimensional nature of the groundwater system.

This was particularly critical in the older alluvium and Nogales Formation. As discussed previously, sparse aquifer specific data were available in the model area particularly in the older alluvium and Nogales Formation.

2. Hydraulic heads computed within each model cell represent the average head within the volume of that cell. Model cell size is critical to the accuracy of simulating the groundwater system. Each model cell covers 10 acres each. In general, the smaller the cell size the more accurate the simulated water level. Since the area of younger alluvium within the microbasin model is so limited, some cell sizes may still be too large.
3. The accuracy of the model to simulate long-term water level changes due to stresses on the groundwater system is comparatively tested and will be proven with time and additional model use. However, the model has reasonably simulated the groundwater level changes for the modeling period 1997-2002. It is assumed the model is sufficiently accurate to compare and evaluate the results from scenario simulations to determine the volume of water, which is recharged in the microbasins during flow events, and determine the volume of water that exits the model area to the NIWTP model area. All predictive scenarios will utilize the model with monthly stress periods.

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Appendix A - Stress Period Days and Dates

Stress Period Number	Begin Date	End Date	Begin Model Day	End Model Day	Days in Stress Period
1	10/01/97	10/31/97	0	31	31
2	10/31/97	11/30/97	31	61	30
3	11/30/97	12/31/97	61	92	31
4	12/31/97	01/31/98	92	123	31
5	01/31/98	02/04/98	123	127	4
6	02/04/98	02/28/98	127	151	24
7	02/28/98	03/05/98	151	156	5
8	03/05/98	03/28/98	156	179	23
9	03/28/98	03/31/98	179	182	3
10	03/31/98	04/09/98	182	191	9
11	04/09/98	04/30/98	191	212	21
12	04/30/98	05/12/98	212	224	12
13	05/12/98	05/31/98	224	243	19
14	05/31/98	06/30/98	243	273	30
15	06/30/98	07/20/98	273	293	20
16	07/20/98	07/23/98	293	296	3
17	07/23/98	07/29/98	296	302	6
18	07/29/98	07/31/98	302	304	2
19	07/31/98	08/19/98	304	323	19
20	08/19/98	08/31/98	323	335	12
21	08/31/98	09/30/98	335	365	30
22	09/30/98	10/31/98	365	396	31
23	10/31/98	11/30/98	396	426	30
24	11/30/98	12/31/98	426	457	31
25	12/31/98	01/31/99	457	488	31
26	01/31/99	02/28/99	488	516	28
27	02/28/99	03/31/99	516	547	31
28	03/31/99	04/30/99	547	577	30
29	04/30/99	05/31/99	577	608	31
30	05/31/99	06/30/99	608	638	30
31	06/30/99	07/22/99	638	660	22
32	07/22/99	07/31/99	660	669	9
33	07/31/99	08/12/99	669	681	12
34	08/12/99	08/27/99	681	696	15
35	08/27/99	08/31/99	696	700	4
36	08/31/99	09/07/99	700	707	7
37	09/07/99	09/30/99	707	730	23
38	09/30/99	10/31/99	730	761	31
39	10/31/99	11/30/99	761	791	30
40	11/30/99	12/31/99	791	822	31
41	12/31/99	01/31/00	822	853	31
42	01/31/00	02/28/00	853	881	28
43	02/28/00	03/31/00	881	912	31

Stress Period Number	Begin Date	End Date	Begin Model Day	End Model Day	Days in Stress Period
44	03/31/00	04/30/00	912	942	30
45	04/30/00	05/31/00	942	973	31
46	05/31/00	06/30/00	973	1003	30
47	06/30/00	07/07/00	1003	1010	7
48	07/07/00	07/31/00	1010	1034	24
49	07/31/00	08/05/00	1034	1039	5
50	08/05/00	08/12/00	1039	1046	7
51	08/12/00	08/28/00	1046	1062	16
52	08/28/00	08/31/00	1062	1065	3
53	08/31/00	09/30/00	1065	1095	30
54	09/30/00	10/10/00	1095	1105	10
55	10/10/00	10/12/00	1105	1107	2
56	10/12/00	10/22/00	1107	1117	10
57	10/22/00	10/23/00	1117	1118	1
58	10/23/00	10/31/00	1118	1126	8
59	10/31/00	11/12/00	1126	1138	12
60	11/12/00	11/30/00	1138	1156	18
61	11/30/00	12/15/00	1156	1171	15
62	12/15/00	12/31/00	1171	1187	16
63	12/31/00	01/31/01	1187	1218	31
64	01/31/01	02/28/01	1218	1246	28
65	02/28/01	03/31/01	1246	1277	31
66	03/31/01	04/05/01	1277	1282	5
67	04/05/01	04/08/01	1282	1285	3
68	04/08/01	04/17/01	1285	1294	9
69	04/17/01	04/30/01	1294	1307	13
70	04/30/01	05/31/01	1307	1338	31
71	05/31/01	06/30/01	1338	1368	30
72	06/30/01	07/31/01	1368	1399	31
73	07/31/01	08/27/01	1399	1426	27
74	08/27/01	08/29/01	1426	1428	2
75	08/29/01	08/31/01	1428	1430	2
76	08/31/01	09/30/01	1430	1460	30
77	09/30/01	10/31/01	1460	1491	31
78	10/31/01	11/30/01	1491	1521	30
79	11/30/01	12/31/01	1521	1552	31
80	12/31/01	01/31/02	1552	1583	31
81	01/31/02	02/28/02	1583	1611	28
82	02/28/02	03/31/02	1611	1642	31
83	03/31/02	04/30/02	1642	1672	30
84	04/30/02	05/31/02	1672	1703	31
85	05/31/02	06/30/02	1703	1733	30
86	06/30/02	07/31/02	1733	1764	31
87	07/31/02	08/04/02	1764	1768	4

Stress Period Number	Begin Date	End Date	Begin Model Day	End Model Day	Days in Stress Period
88	08/04/02	08/06/02	1768	1770	2
89	08/06/02	08/17/02	1770	1781	11
90	08/17/02	08/19/02	1781	1783	2
91	08/19/02	08/31/02	1783	1795	12
92	08/31/02	09/09/02	1795	1804	9
93	09/09/02	09/10/02	1804	1805	1
94	09/10/02	09/30/02	1805	1825	20

Appendix B - Stream-Routing Package Input

Stream-Routing Package Input to Main Channel of Santa Cruz River near USGS Gage 09480500							
Begin Day	**End Day**	**Stage (feet)**	**Stream Top Elevation (feet)**	**Stream Bot Elevation (feet)**	**Width (feet)**	**Flow (cfd)**	**Kz (ft/day)**
0	127	3711.25	3711	3706	2.61	8894	2
127	156	3712.5	3711	3706	56.74	6018386	2
156	179	3711.25	3711	3706	5.2	38166	2
179	191	3713	3711	3706	64.47	7887600	2
191	293	3711.5	3711	3706	10.57	171335	2
293	296	3712.5	3711	3706	64.04	7776000	2
296	302	3711	3711	3706	0	0	2
302	323	3712	3711	3706	32.07	1797573	2
323	365	3711.25	3711	3706	1.14	1523	2
365	488	3711.25	3711	3706	0	0	2
488	577	3711.25	3711	3706	0.14	19	2
577	660	3711.25	3711	3706	3.3	14542	2
660	681	3712.5	3711	3706	56.88	6050222	2
681	696	3711.5	3711	3706	10.57	171302	2
696	707	3713	3711	3706	94.78	17835316	2
707	730	3712	3711	3706	31.81	1766692	2
730	1003	3711.5	3711	3706	8.53	108756	2
1003	1010	3711.5	3711	3706	22.67	862149	2
1010	1039	3711.25	3711	3706	3.4	15522	2
1039	1046	3712.5	3711	3706	62.82	7464837	2
1046	1062	3711.25	3711	3706	7.35	79326	2
1062	1065	3712	3711	3706	40.25	2908800	2
1065	1105	3711.25	3711	3706	1.75	3780	2
1105	1107	3714	3711	3706	251.23	1.41E+08	2
1107	1117	3713	3711	3706	100.68	20269440	2
1117	1118	3714	3711	3706	278.26	1.75E+08	2
1118	1138	3713	3711	3706	111.58	25198560	2
1138	1156	3712.5	3711	3706	66.15	8328000	2
1156	1171	3712.5	3711	3706	45.64	3795840	2
1171	1246	3712	3711	3706	34.56	2105856	2
1246	1282	3711.5	3711	3706	22.43	843360	2
1282	1285	3713	3711	3706	87.59	15091200	2
1285	1294	3712.5	3711	3706	50.85	4771200	2
1294	1426	3711.5	3711	3706	11.74	213899	2
1426	1428	3712	3711	3706	38.12	2592000	2
1428	1611	3711.25	3711	3706	6.87	68827	2
1611	1768	3711.25	3711	3706	3	11936	2
1768	1770	3712.5	3711	3706	45.43	3758400	2
1770	1781	3711	3711	3706	0.05	2	2

1781	1783	3712.5	3711	3706	48.06	4233600	2
1783	1804	3711.25	3711	3706	5.22	38510	2
1804	1805	3712.5	3711	3706	48.98	4406400	2
1805	1825	3711.25	3711	3706	4.8	32227	2

Stream-Routing Package Input to Brickwood Canyon							
Begin Day	End Day	Stage (feet)	Stream Top Elevation (feet)	Stream Bot Elevation (feet)	Width (feet)	Flow (cfd)	Kz (ft/day)
0	127	3720.25	3720	3715	0.465349	229.92	2
127	156	3720.5	3720	3715	10.09916	155583.8	2
156	179	3720.25	3720	3715	0.925726	986.65	2
179	191	3720.5	3720	3715	11.47498	203905.6	2
191	293	3720.25	3720	3715	1.881208	4429.25	2
293	296	3720.5	3720	3715	11.39803	201020.6	2
296	302	3720.25	3720	3715	0	0	2
302	323	3720.25	3720	3715	5.707918	46469.81	2
323	365	3720.25	3720	3715	0.202249	39.37	2
365	488	3720	3720	3715	0	0	2
488	577	3720.25	3720	3715	0.025696	0.5	2
577	660	3720.25	3720	3715	0.591067	381.53	2
660	681	3720.5	3720	3715	10.19526	158735.7	2
681	696	3720.25	3720	3715	1.894211	4494.34	2
696	707	3720.5	3720	3715	16.98637	467933.3	2
707	730	3720.25	3720	3715	5.701053	46351.52	2
730	1003	3720.25	3720	3715	1.522825	2831.06	2
1003	1010	3720.25	3720	3715	4.04779	22442.77	2
1010	1039	3720.25	3720	3715	0.607301	404.06	2
1039	1046	3720.5	3720	3715	11.21699	194318.7	2
1046	1062	3720.25	3720	3715	1.312019	2064.95	2
1062	1065	3720.25	3720	3715	7.187895	75719.57	2
1065	1105	3720.25	3720	3715	0.311693	98.4	2
1105	1107	3721.5	3720	3715	44.83325	3654379	2
1107	1117	3720.5	3720	3715	17.96602	526931.3	2
1117	1118	3721.5	3720	3715	49.65579	4537090	2
1118	1138	3720.5	3720	3715	19.9109	655070.4	2
1138	1156	3720.5	3720	3715	11.80431	216497.5	2
1156	1171	3720.5	3720	3715	8.145362	98677.96	2
1171	1246	3720.25	3720	3715	6.167146	54744.55	2
1246	1282	3720.25	3720	3715	4.003359	21924.28	2
1282	1285	3720.5	3720	3715	15.62984	392316	2
1285	1294	3720.5	3720	3715	9.074217	124033.8	2
1294	1426	3720.25	3720	3715	2.094526	5560.59	2
1426	1428	3720.25	3720	3715	6.802674	67382.52	2
1428	1611	3720.25	3720	3715	1.226173	1789.26	2
1611	1768	3720.25	3720	3715	0.534726	308.6	2
1768	1770	3720.5	3720	3715	8.086264	97167.89	2
1770	1781	3720.25	3720	3715	1.304146	2038.8	2
1781	1783	3720.5	3720	3715	8.553894	109453.5	2

1783	1804	3720.25	3720	3715	0.929689	995.61	2
1804	1805	3720.5	3720	3715	8.717017	113921	2
1805	1825	3720.25	3720	3715	0.854701	833.19	2

Stream Routing Package Input to Providencia Canyon							
Begin Day	End Day	Stage (feet)	Stream Top Elevation (feet)	Stream Bot Elevation (feet)	Width (feet)	Flow (cfd)	Kz (ft/day)
0	127	3670.25	3670	3665	0.93923	1017.374	2
127	156	3670.5	3670	3665	20.3835	688435.8	2
156	179	3670.25	3670	3665	1.868426	4365.762	2
179	191	3671	3670	3665	23.16038	902253	2
191	293	3670.25	3670	3665	3.796911	19598.8	2
293	296	3671	3670	3665	23.00506	889487.2	2
296	302	3670	3670	3665	0	0	2
302	323	3670.5	3670	3665	11.5205	205622.2	2
323	365	3670.25	3670	3665	0.408206	174.2141	2
365	488	3670	3670	3665	0	0	2
488	577	3670.25	3670	3665	0.051864	2.205748	2
577	660	3670.25	3670	3665	1.192972	1688.21	2
660	681	3670.5	3670	3665	20.57746	702382.3	2
681	696	3670.25	3670	3665	3.823155	19886.79	2
696	707	3671	3670	3665	34.2842	2070537	2
707	730	3670.5	3670	3665	11.50664	205098.8	2
730	1003	3670.25	3670	3665	3.073573	12527.03	2
1003	1010	3670.5	3670	3665	8.169801	99306	2
1010	1039	3670.25	3670	3665	1.225738	1787.915	2
1039	1046	3670.5	3670	3665	22.63965	859832.1	2
1046	1062	3670.25	3670	3665	2.648095	9137.112	2
1062	1065	3670.5	3670	3665	14.50759	335048.2	2
1065	1105	3670.25	3670	3665	0.629102	435.3967	2
1105	1107	3672	3670	3665	90.48858	16170098	2
1107	1117	3671	3670	3665	36.26147	2331595	2
1117	1118	3672	3670	3665	100.2221	20075966	2
1118	1138	3671	3670	3665	40.18689	2898592	2
1138	1156	3671	3670	3665	23.82506	957970.3	2
1156	1171	3670.5	3670	3665	16.44008	436635.7	2
1171	1246	3670.5	3670	3665	12.44738	242236.7	2
1246	1282	3670.5	3670	3665	8.080125	97011.75	2
1282	1285	3671	3670	3665	31.54628	1735942	2
1285	1294	3670.5	3670	3665	18.31482	548831.4	2
1294	1426	3670.25	3670	3665	4.227457	24604.8	2
1426	1428	3670.5	3670	3665	13.73008	298157.9	2
1428	1611	3670.25	3670	3665	2.47483	7917.206	2
1611	1768	3670.25	3670	3665	1.079257	1365.502	2
1768	1770	3670.5	3670	3665	16.3208	429953.9	2
1770	1781	3670.25	3670	3665	2.632206	9021.393	2
1781	1783	3670.5	3670	3665	17.26464	484315.8	2

1783	1804	3670.25	3670	3665	1.876425	4405.439	2
1804	1805	3670.5	3670	3665	17.59387	504083.8	2
1805	1825	3670.25	3670	3665	1.725074	3686.731	2

Stream-Routing Package Input to Guevavi Canyon							
Begin Day	End Day	Stage (feet)	Stream Top Elevation (feet)	Stream Bot Elevation (feet)	Width (feet)	Flow (cfd)	Kz (ft/day)
0	127	3557.25	3557	3552	0.812728	748.91	2
127	156	3557.5	3557	3552	17.63811	506771.5	2
156	179	3557.25	3557	3552	1.616775	3213.73	2
179	191	3557.5	3557	3552	20.04098	664166.6	2
191	293	3557.25	3557	3552	3.285516	14427.07	2
293	296	3557.5	3557	3552	19.90658	654769.5	2
296	302	3557	3557	3552	0	0	2
302	323	3557.5	3557	3552	9.968837	151362.6	2
323	365	3557.25	3557	3552	0.353222	128.24	2
365	488	3557	3557	3552	0	0	2
488	577	3557.25	3557	3552	0.04483	1.62	2
577	660	3557.25	3557	3552	1.032296	1242.73	2
660	681	3557.5	3557	3552	17.80594	517037.8	2
681	696	3557.25	3557	3552	3.308226	14639.07	2
696	707	3558	3557	3552	29.66656	1524164	2
707	730	3557.5	3557	3552	9.956846	150977.4	2
730	1003	3557.25	3557	3552	2.659602	9221.4	2
1003	1010	3557.25	3557	3552	7.069434	73101.15	2
1010	1039	3557.25	3557	3552	1.060647	1316.12	2
1039	1046	3557.5	3557	3552	19.59039	632939.8	2
1046	1062	3557.25	3557	3552	2.291431	6726.01	2
1062	1065	3557.5	3557	3552	12.55361	246635.7	2
1065	1105	3557.25	3557	3552	0.544367	320.5	2
1105	1107	3559	3557	3552	78.30093	11903135	2
1107	1117	3558	3557	3552	31.37752	1716334	2
1117	1118	3559	3557	3552	86.72347	14778324	2
1118	1138	3558	3557	3552	34.77423	2133712	2
1138	1156	3557.5	3557	3552	20.61614	705181.3	2
1156	1171	3557.5	3557	3552	14.22581	321416.4	2
1171	1246	3557.5	3557	3552	10.77087	178315.4	2
1246	1282	3557.25	3557	3552	6.991837	71412.31	2
1282	1285	3558	3557	3552	27.2974	1277862	2
1285	1294	3557.5	3557	3552	15.84805	404005.9	2
1294	1426	3557.25	3557	3552	3.658073	18112.09	2
1426	1428	3557.5	3557	3552	11.88082	219480.1	2
1428	1611	3557.25	3557	3552	2.141503	5828.02	2
1611	1768	3557.25	3557	3552	0.933893	1005.17	2
1768	1770	3557.5	3557	3552	14.1226	316497.7	2
1770	1781	3557.25	3557	3552	2.277682	6640.83	2
1781	1783	3557.5	3557	3552	14.93931	356514.7	2

1783	1804	3557.25	3557	3552	1.623695	3242.93	2
1804	1805	3557.5	3557	3552	15.22421	371066.3	2
1805	1825	3557.25	3557	3552	1.49273	2713.88	2

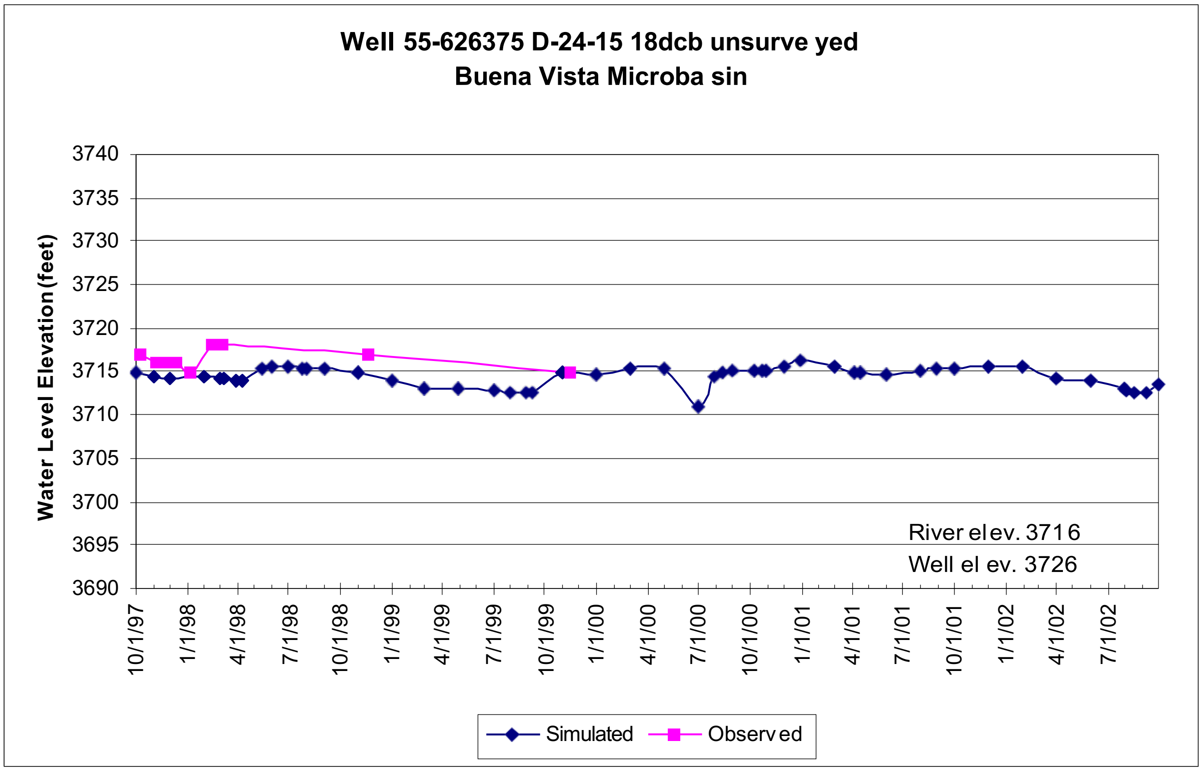
Appendix C – ADWR Stream Seepage Measurements, USGS Flow Estimates and Model Simulated Flow Estimates

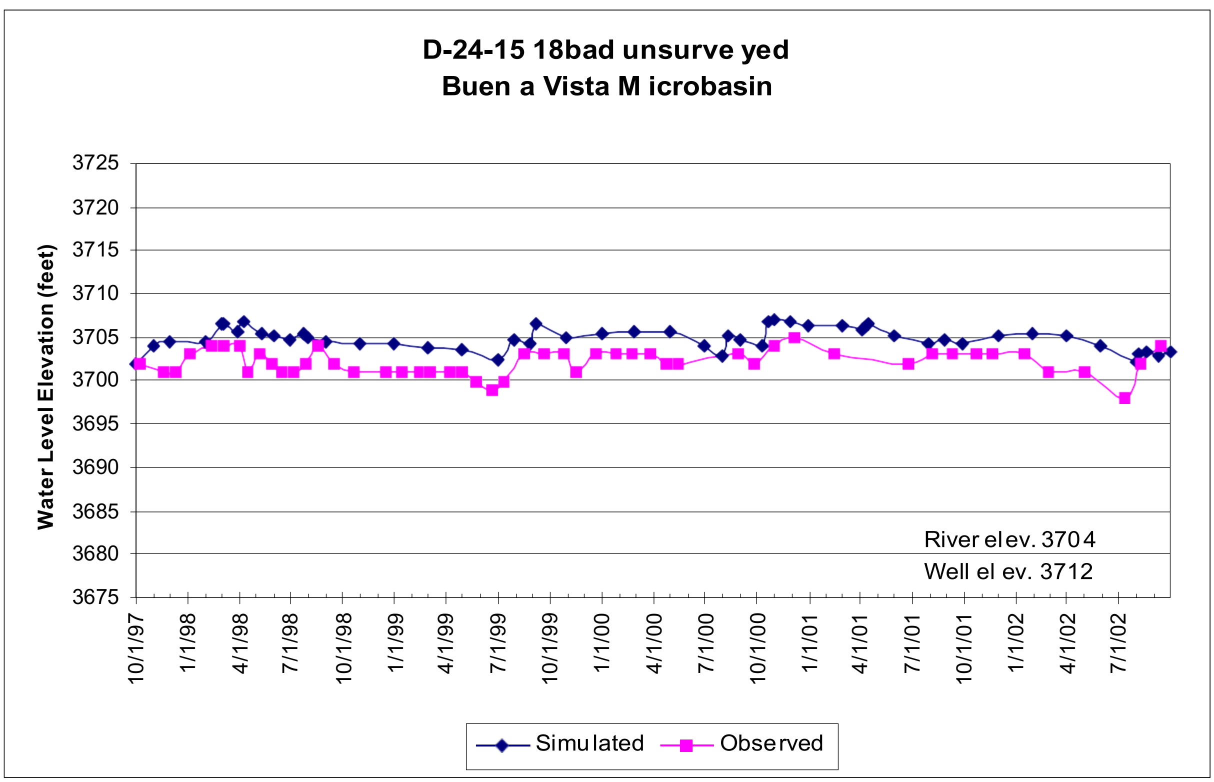
Observed[1] and Simulated Santa Cruz River Flows (cfs)								
ADWR[2] Measurement Date	ADWR Buena Vista	Daily Mean Flow at USGS[3] Gage 09480500	ADWR Kino Springs	ADWR Highway 82	ADWR Guevavi Narrows	Model Simulation[4] At Guevavi Narrows	Model Stress Period Begin Day	Model Stress Period End Day
10/7/1997	0	0	0	0	0	0	10/1/97	10/31/97
12/11/1997	0	0	0	0	0	0	11/30/97	12/31/97
1/5/1998	0	0	0	0	0	0	1/31/98	2/4/98
2/13/1998	36.87	28	18.35	5.4	0	0	2/4/98	2/28/98
3/5/1998	23.47	2.3	23.42	1.06		0.5	2/28/98	3/5/98
4/1/1998	186.06	164			124.61	1.2	3/31/98	4/9/98
4/15/1998	15.87	11	12.84	8.56	0	0.7	4/9/30	4/30/98
5/6/1998	1	1.1	0	0	0.5	0.7	4/30/98	5/12/98
5/27/1998	0	0	0	0	1	0.7	5/12/98	5/31/98
6/10/1998	0	0				0.6	5/31/98	6/30/98
6/15/1998		0	0	0	0.5	0.6	5/31/98	6/30/98
7/7/1998	0	0	0	0	0.5	0.5	6/30/98	7/20/98
7/29/1998	0	0	0	0	0.5	0	7/23/98	7/29/98
9/16/1998	0	0	0	0	0	0.1	8/31/98	9/30/98
11/18/1998	0	0	0	0	0	0	10/31/98	11/30/98
12/15/1998	0	0	0	0	0	0	11/30/98	12/31/98
1/12/1999	0	0	0	0	0	0	12/31/98	1/31/99
3/3/1999	0	0	0		0	0.03	2/28/99	3/31/99
4/6/1999	0	0		0	0	0.03	3/31/99	4/30/99
4/30/1999	0	0	0	0	0	0.03	3/31/99	4/30/99
5/25/1999	0	0	0	0	0	0.4	4/30/99	5/31/99
6/24/1999	0	0	0	0	0	0.3	5/31/99	6/30/99
7/13/1999	0	0	0	0	0	0.2	6/30/99	7/22/99
8/17/1999	55.44	6.7	55.37	18.6	0	0.5	8/12/99	8/27/99
9/21/1999	28.82	13		23.37	2.69	1	9/7/99	9/30/99
1/24/2000	0.81	1.1				0.7	12/31/00	1/31/00
2/12/2001	nd	22		10.83		0.7	1/31/00	2/28/00

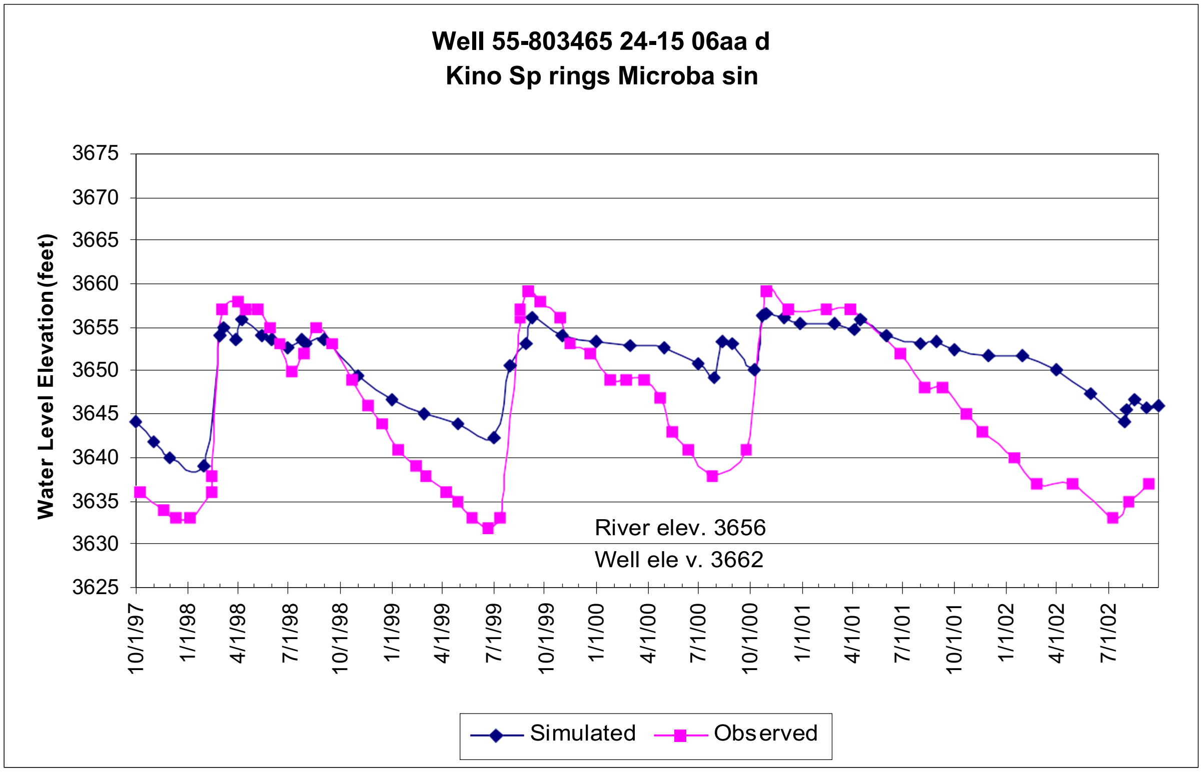
[1] Location of ADWR seepage run measurements are shown on Figure 5-.
[2] ADWR measurement was a single point in time and not necessarily a reflection of the entire day.
[3] USGS flows are based on stream stage measurements every 15 minutes and converted to flows using a rating curve.
[4] Model simulation value is the average for the stress period and not necessarily accurate for a specific time during a specific day.

Appendix D – Model Simulation vs. Observed Hydrographs

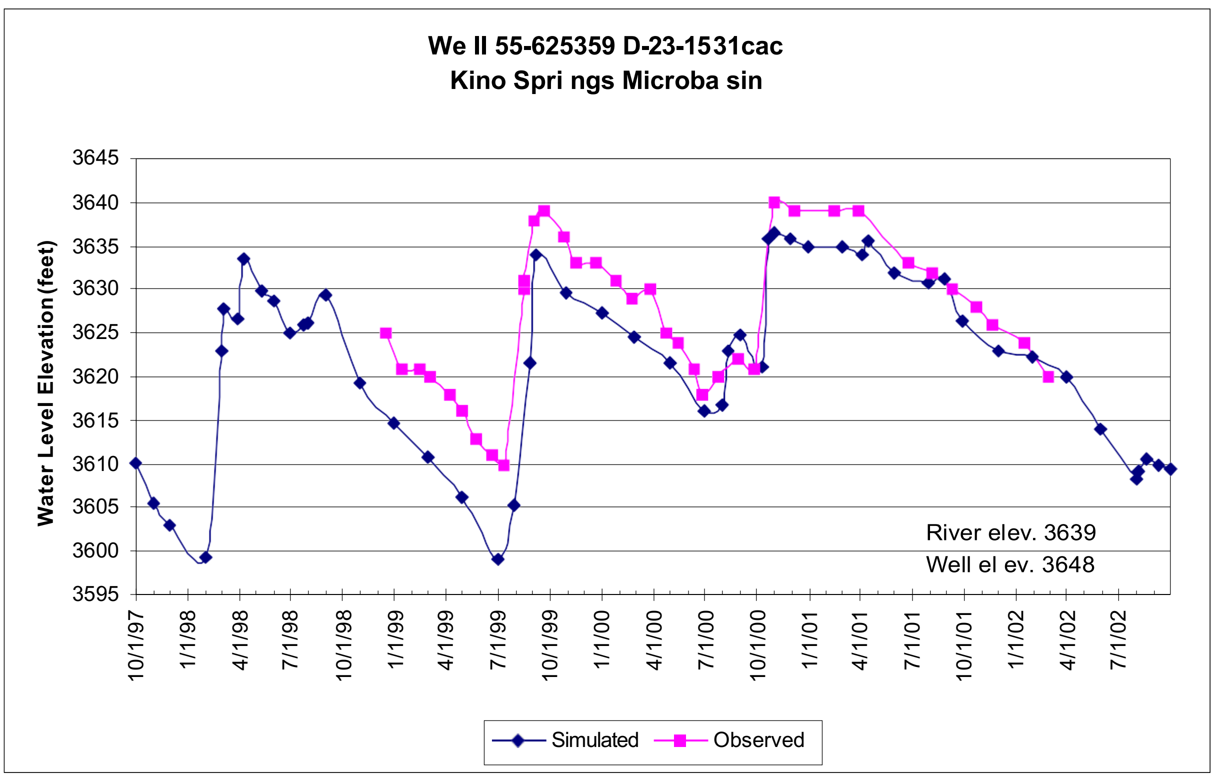
Younger Alluvium



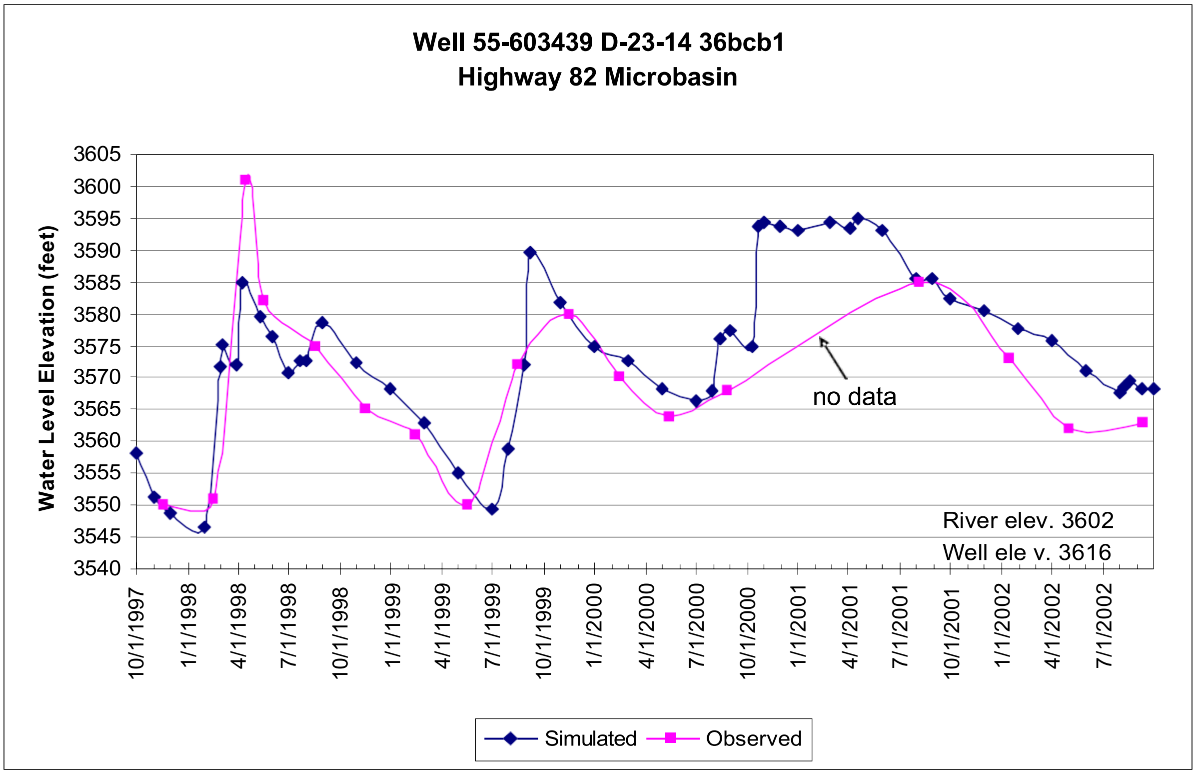




Well 55-803465 24-15 06aa d
Kino Sp rings Microba sin
Water Level Elevation (feet)
3675
3670
3665
3660
3655
3650
3645
3640
3635
3630
3625
River elev. 3656
Well ele v. 3662
10/1/97
1/1/98
4/1/98
7/1/98
10/1/98
1/1/99
4/1/99
7/1/99
10/1/99
1/1/00
4/1/00
7/1/00
10/1/00
1/1/01
4/1/01
7/1/01
10/1/01
1/1/02
4/1/02
7/1/02
Simulated
Obs erved



We ll 55-625359 D-23-1531cac
Kino Spri ngs Microba sin
Water Level Elevation (feet)
3645
3640
3635
3630
3625
3620
3615
3610
3605
3600
3595
River elev. 3639
Well el ev. 3648
10/1/97
1/1/98
4/1/98
7/1/98
10/1/98
1/1/99
4/1/99
7/1/99
10/1/99
1/1/00
4/1/00
7/1/00
10/1/00
1/1/01
4/1/01
7/1/01
10/1/01
1/1/02
4/1/02
7/1/02
Simulated
Observed


Well 55-603439 D-23-14 36bcb1
Highway 82 Microbasin
Water Level Elevation (feet)
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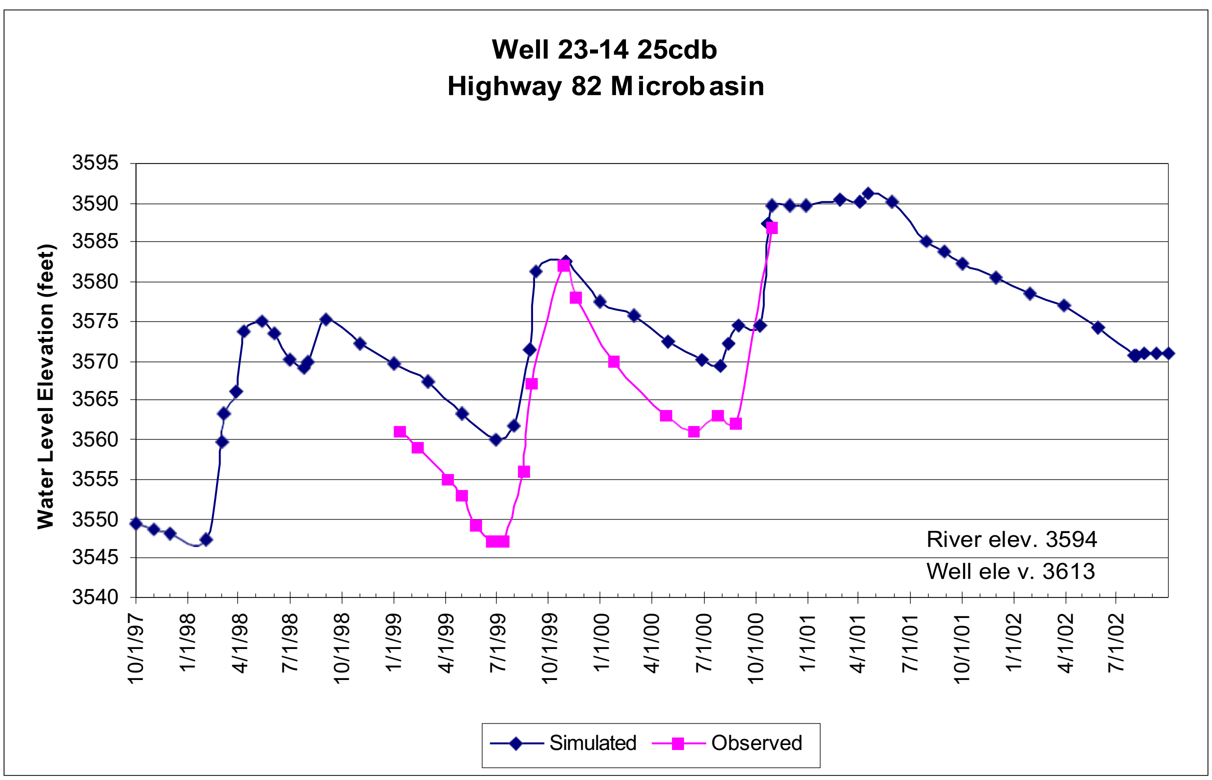
3600
3595
3590
3585
3580
3575
3570
3565
3560
3555
3550
3545
3540
10/1/1997
1/1/1998
4/1/1998
7/1/1998
10/1/1998
1/1/1999
4/1/1999
7/1/1999
10/1/1999
1/1/2000
4/1/2000
7/1/2000
10/1/2000
1/1/2001
4/1/2001
7/1/2001
10/1/2001
1/1/2002
4/1/2002
7/1/2002
no data
River elev. 3602
Well ele v. 3616
Simulated
Observed


Well 23-14 25cdb
Highway 82 Microbasin
Water Level Elevation (feet)
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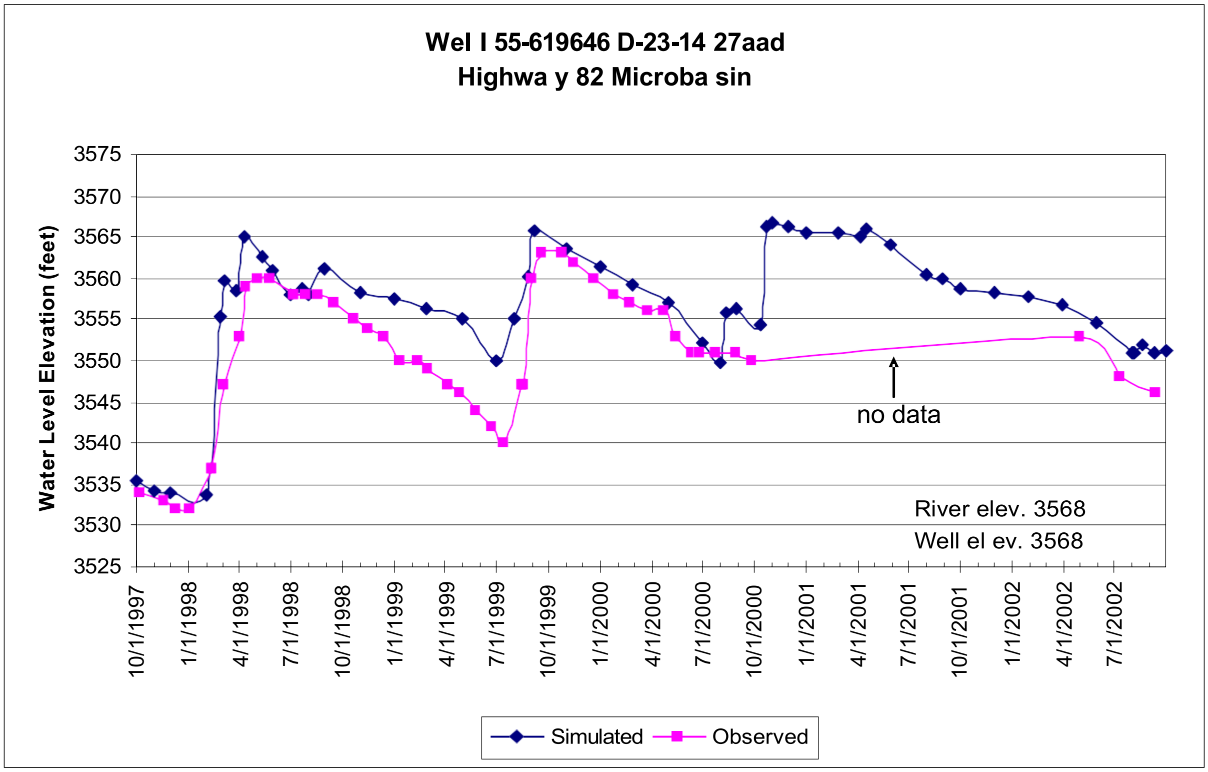
3590
3585
3580
3575
3570
3565
3560
3555
3550
3545
3540
10/1/97
1/1/98
4/1/98
7/1/98
10/1/98
1/1/99
4/1/99
7/1/99
10/1/99
1/1/00
4/1/00
7/1/00
10/1/00
1/1/01
4/1/01
7/1/01
10/1/01
1/1/02
4/1/02
7/1/02
River elev. 3594
Well ele v. 3613
Simulated
Observed



Wel l 55-619646 D-23-14 27aad
Highwa y 82 Microba sin
Water Level Elevation (feet)
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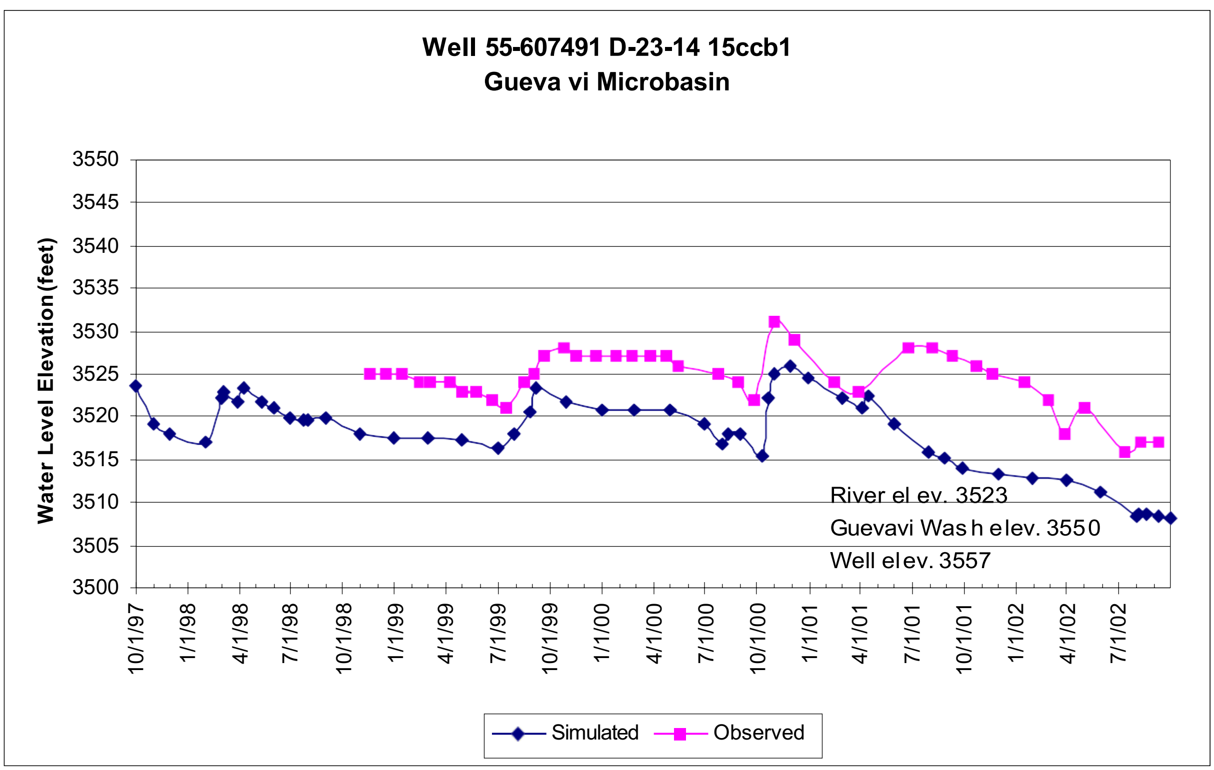
3570
3565
3560
3555
3550
3545
3540
3535
3530
3525
no data
River elev. 3568
Well el ev. 3568
10/1/1997
1/1/1998
4/1/1998
7/1/1998
10/1/1998
1/1/1999
4/1/1999
7/1/1999
10/1/1999
1/1/2000
4/1/2000
7/1/2000
10/1/2000
1/1/2001
4/1/2001
7/1/2001
10/1/2001
1/1/2002
4/1/2002
7/1/2002
Simulated
Observed



Well 55-607491 D-23-14 15ccb1
Gueva vi Microbasin
Water Level Elevation (feet)
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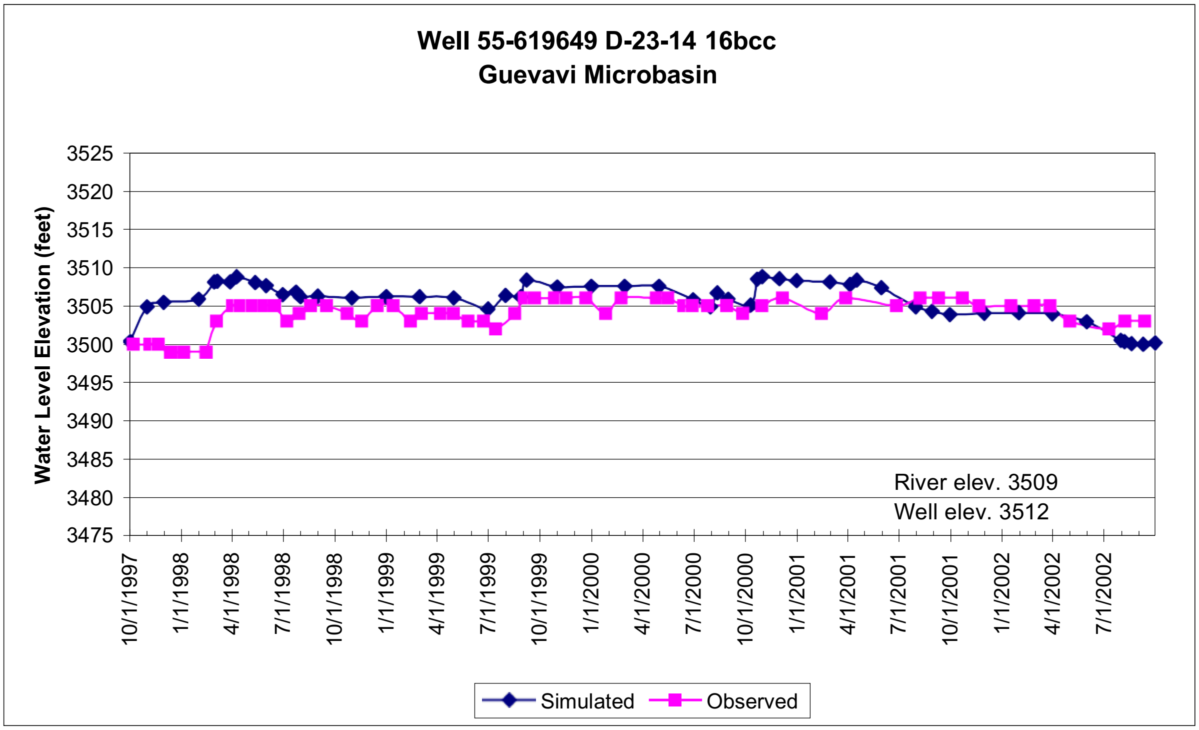
3545
3540
3535
3530
3525
3520
3515
3510
3505
3500
River el ev. 3523
Guevavi Was h elev. 3550
Well el ev. 3557
10/1/97
1/1/98
4/1/98
7/1/98
10/1/98
1/1/99
4/1/99
7/1/99
10/1/99
1/1/00
4/1/00
7/1/00
10/1/00
1/1/01
4/1/01
7/1/01
10/1/01
1/1/02
4/1/02
7/1/02
Simulated
Observed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Guevavi Microbasin
Water Level Elevation (feet)
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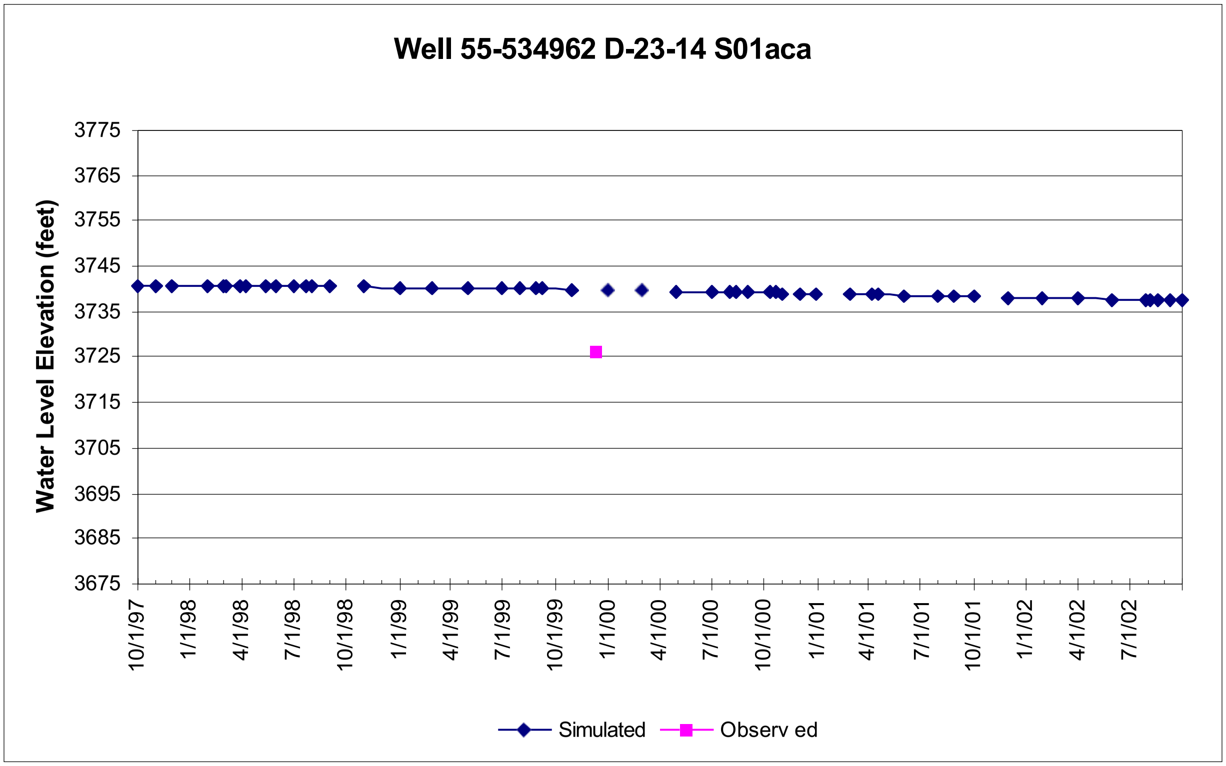
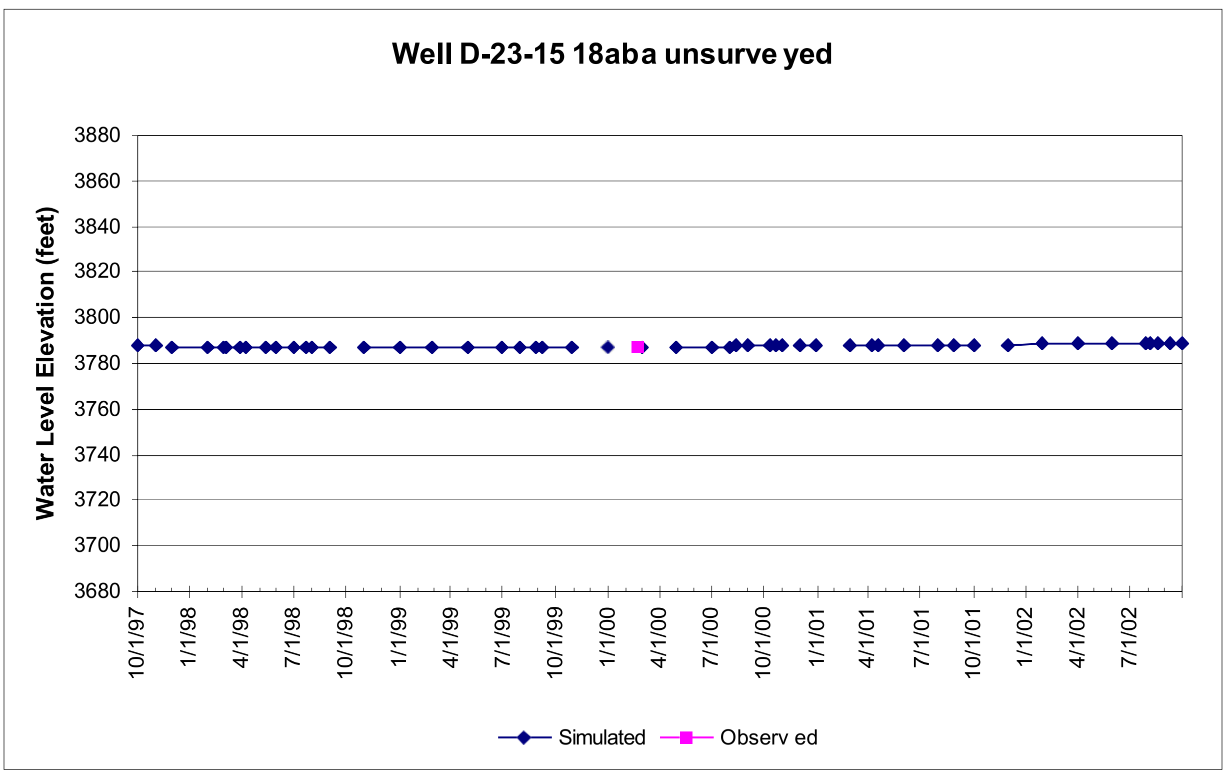
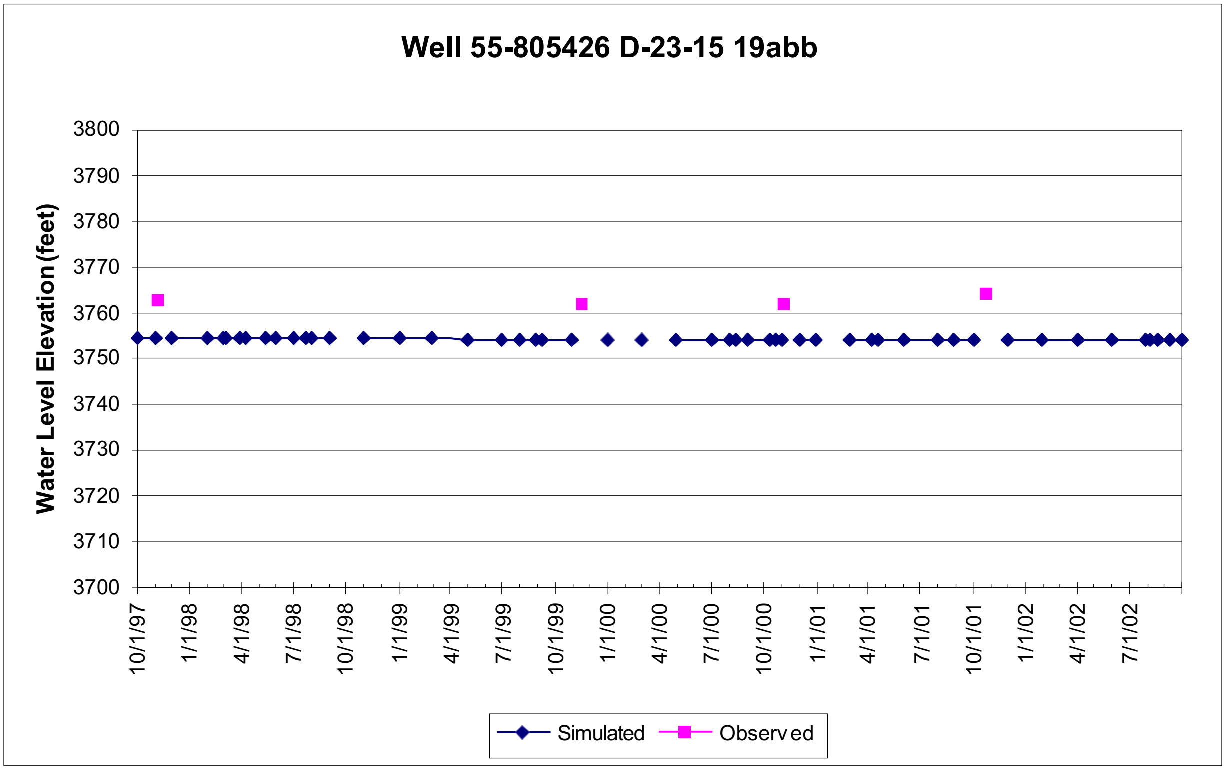
3515
3510
3505
3500
3495
3490
3485
3480
3475
River elev. 3509
Well elev. 3512
10/1/1997
1/1/1998
4/1/1998
7/1/1998
10/1/1998
1/1/1999
4/1/1999
7/1/1999
10/1/1999
1/1/2000
4/1/2000
7/1/2000
10/1/2000
1/1/2001
4/1/2001
7/1/2001
10/1/2001
1/1/2002
4/1/2002
7/1/2002
Simulated
Observed

Older Alluvium and Nogales Formation



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Water Level Elevation (feet)
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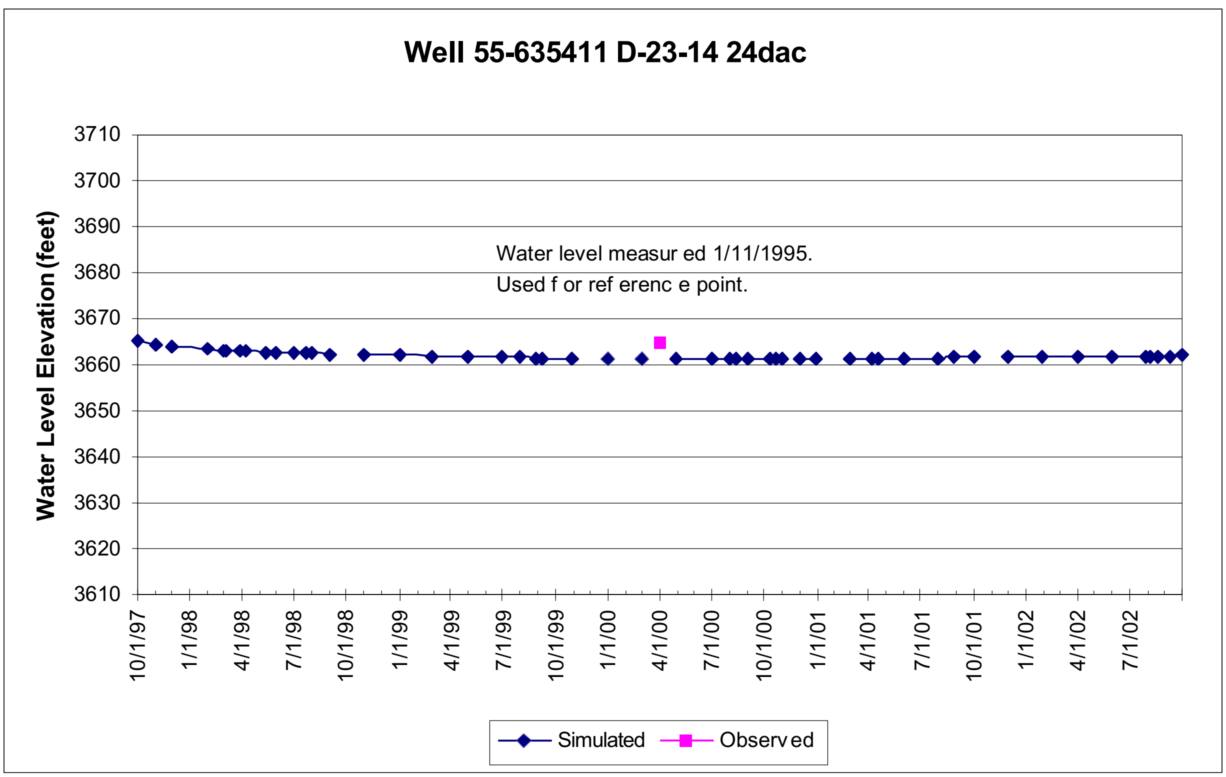
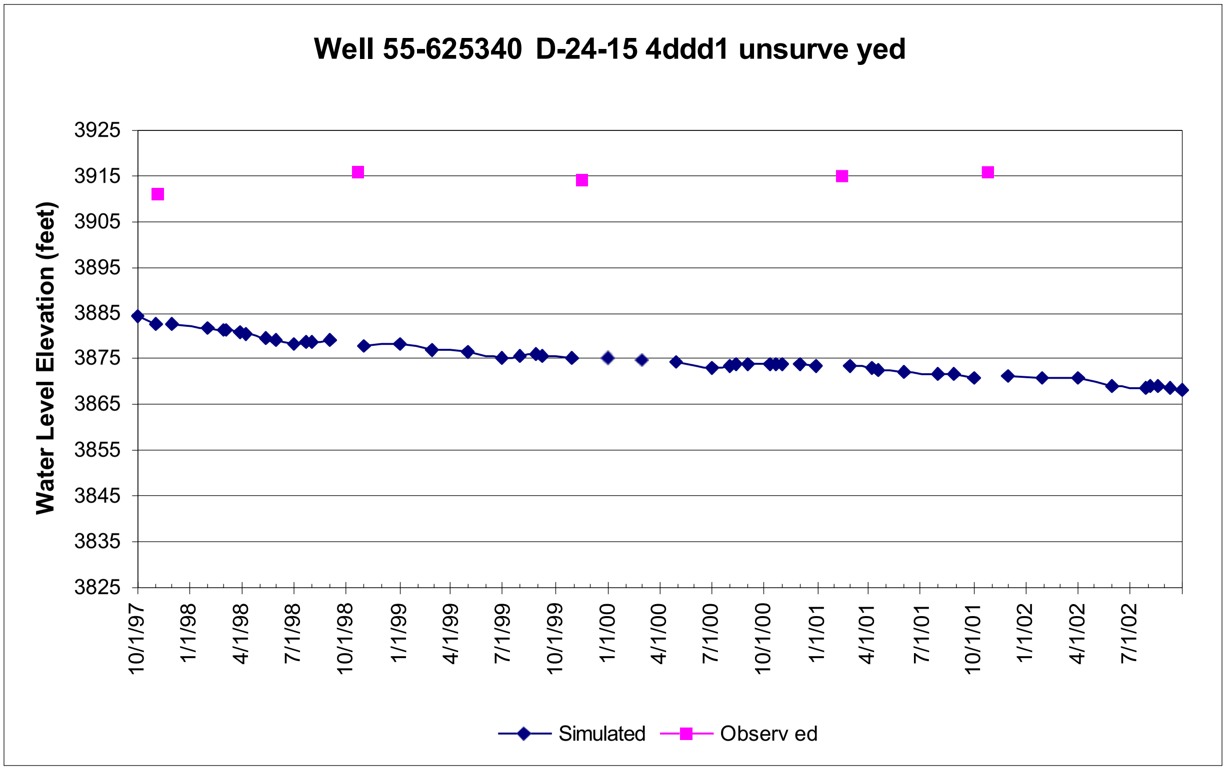
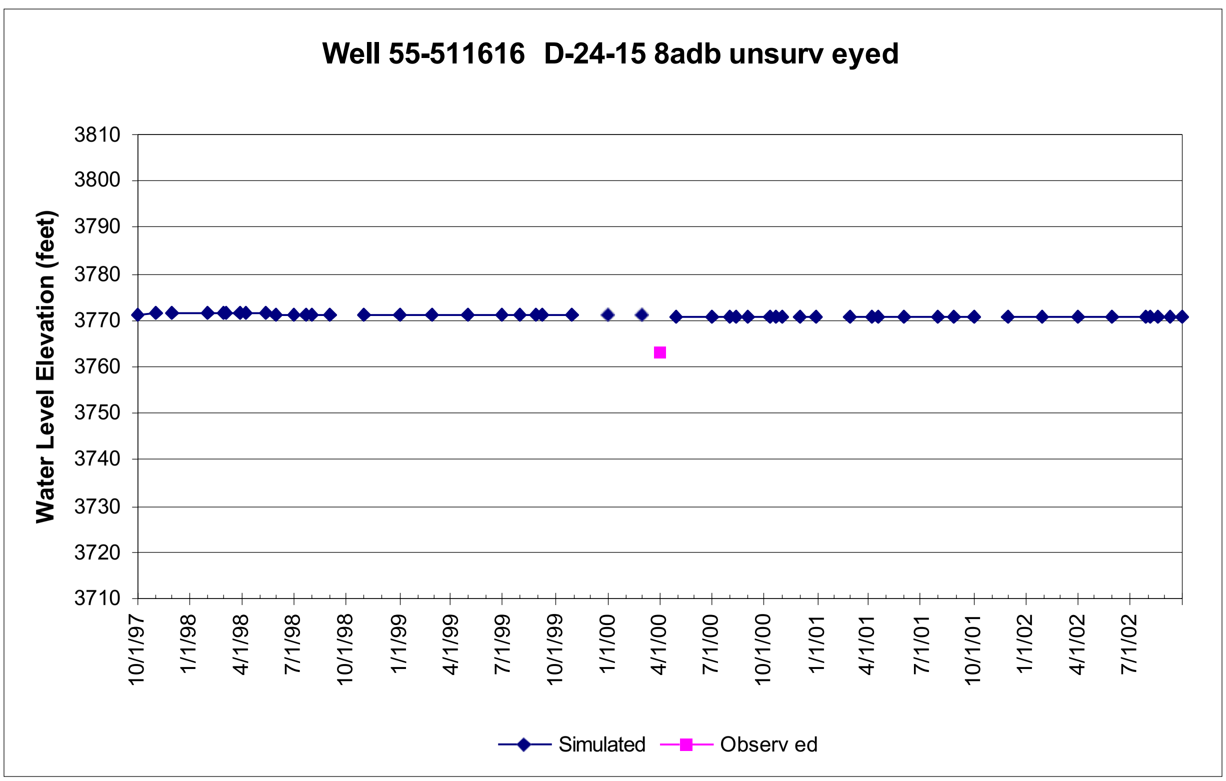
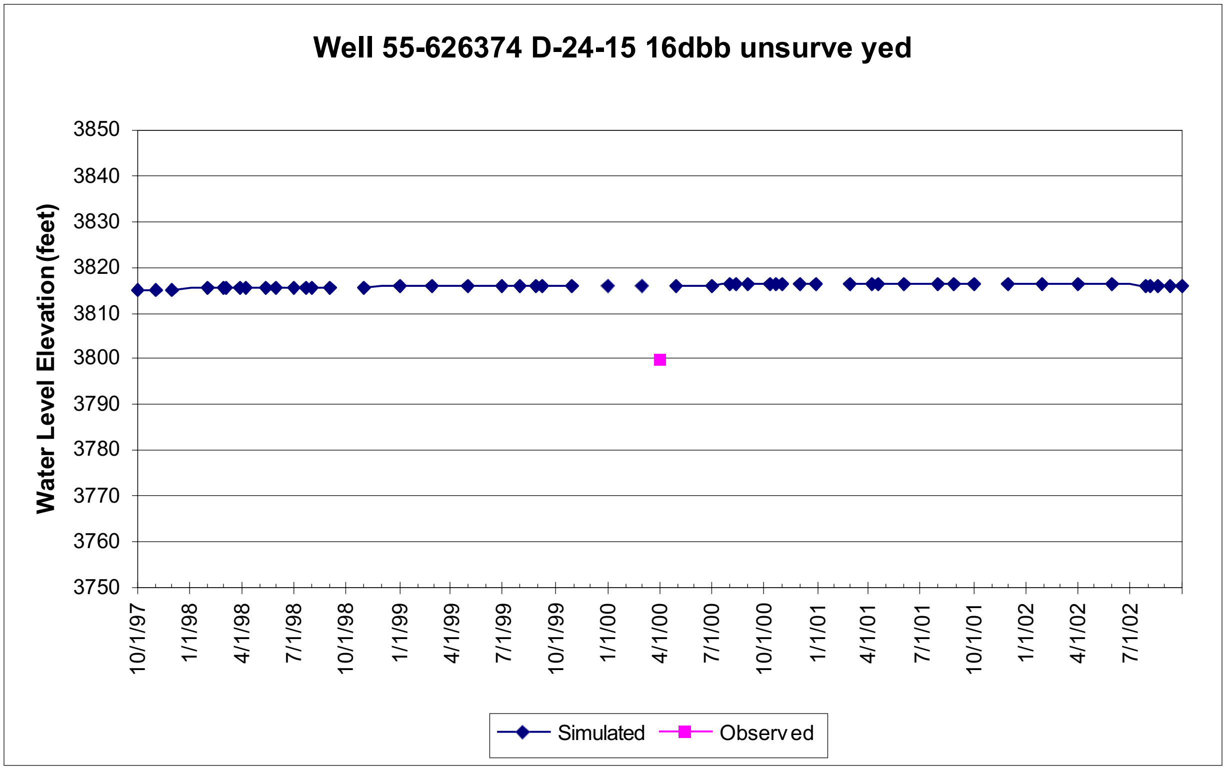
3770
3760
3750
3740
3730
3720
3710
3700
10/1/97
1/1/98
4/1/98
7/1/98
10/1/98
1/1/99
4/1/99
7/1/99
10/1/99
1/1/00
4/1/00
7/1/00
10/1/00
1/1/01
4/1/01
7/1/01
10/1/01
1/1/02
4/1/02
7/1/02
Simulated
Observed

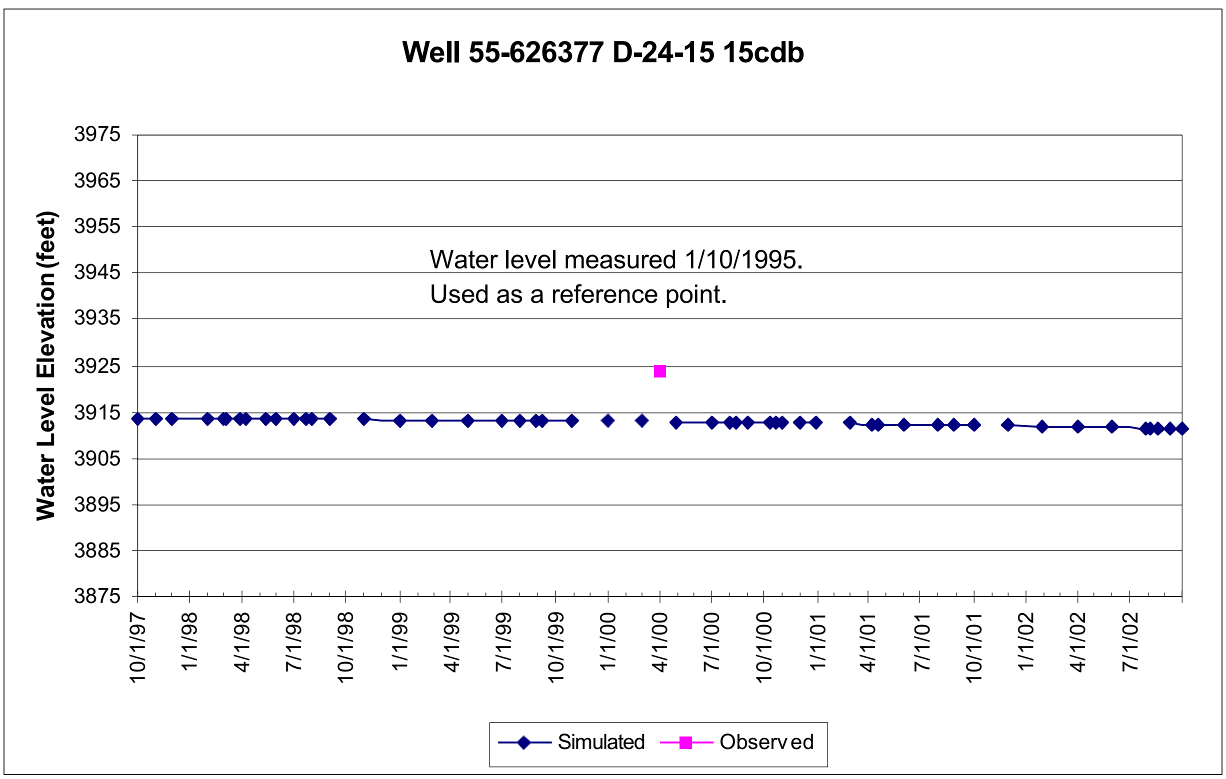

Well 55-635411 D-23-14 24dac
Water Level Elevation (feet)
3710
3700
3690
3680
3670
3660
3650
3640
3630
3620
3610
Water level measured 1/11/1995.
Used for reference point.
10/1/97
1/1/98
4/1/98
7/1/98
10/1/98
1/1/99
4/1/99
7/1/99
10/1/99
1/1/00
4/1/00
7/1/00
10/1/00
1/1/01
4/1/01
7/1/01
10/1/01
1/1/02
4/1/02
7/1/02
Simulated
Observed


Well 55-625340 D-24-15 4ddd1 unsurve yed
Water Level Elevation (feet)
3925
3915
3905
3895
3885
3875
3865
3855
3845
3835
3825
10/1/97
1/1/98
4/1/98
7/1/98
10/1/98
1/1/99
4/1/99
7/1/99
10/1/99
1/1/00
4/1/00
7/1/00
10/1/00
1/1/01
4/1/01
7/1/01
10/1/01
1/1/02
4/1/02
7/1/02
Simulated
Observ ed


Well 55-511616 D-24-15 8adb unsurv eyed
Water Level Elevation (feet)
3810
3800
3790
3780
3770
3760
3750
3740
3730
3720
3710
10/1/97
1/1/98
4/1/98
7/1/98
10/1/98
1/1/99
4/1/99
7/1/99
10/1/99
1/1/00
4/1/00
7/1/00
10/1/00
1/1/01
4/1/01
7/1/01
10/1/01
1/1/02
4/1/02
7/1/02
Simulated
Observ ed



Well 55-626374 D-24-15 16dbb unsurve yed
Water Level Elevation (feet)
3850
3840
3830
3820
3810
3800
3790
3780
3770
3760
3750
10/1/97
1/1/98
4/1/98
7/1/98
10/1/98
1/1/99
4/1/99
7/1/99
10/1/99
1/1/00
4/1/00
7/1/00
10/1/00
1/1/01
4/1/01
7/1/01
10/1/01
1/1/02
4/1/02
7/1/02
Simulated
Observed



Well 55-626377 D-24-15 15cdb
Water Level Elevation (feet)
3975
3965
3955
3945
3935
3925
3915
3905
3895
3885
3875
Water level measured 1/10/1995.
Used as a reference point.
10/1/97
1/1/98
4/1/98
7/1/98
10/1/98
1/1/99
4/1/99
7/1/99
10/1/99
1/1/00
4/1/00
7/1/00
10/1/00
1/1/01
4/1/01
7/1/01
10/1/01
1/1/02
4/1/02
7/1/02
Simulated
Observed